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Materials Engineering and Research Office Report

Cone Penetrometer Versus Casagrande Apparatus to Determine Liquid Limit of Soils

MERO-014

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Abstract	The Casagrande test method and the apparatus for determination of liquid limit of clayey soils has been the universally recognised method for over forty years. In North America, this test method has continued to be the only acceptable test procedure for determination of liquid limit. The test method devised by Casagrande has been superseded in many parts of the world by the Cone Penetrometer. In spite of the standardisation and automation of the Casagrande apparatus, the mechanical adjustments, calibration of the equipment, and test procedures may give rise to significant variations in the test results obtained by different operators using the same piece of equipment . Various agencies and authors have found that the determination of liquid limit by means of the cone penetrometer method offers considerable advantages over the Casagrande apparatus and gives a greater degree of precision between different operators. A study was undertaken to investigate the possibility of substituting the cone penetrometer for the Casagrande apparatus and to establish appropriate factors for use in conjunction with the one-point method to determine the liquid limit of soils found in Ontario. Recommendations are made with respect to adoption of the cone penetrometer method and suitable factors for obtaining liquid limit by the one-point method.

Key Words	Cone Penetrometer, Casagrande apparatus, clay, coefficient of variation, liquid limit, mean, proficiency, reproducibility, shear strength, soil, standard deviation, test method
Distribution	Unrestricted technical audience.

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Executive Summary

The Casagrande apparatus for determination of liquid limit of clayey soils has been the universally recognised equipment for over forty years. In the United States and Canada, this test method has continued to be the only acceptable test procedure for determination of liquid limit. Several shortcomings with the Casagrande apparatus resulted in the development of the cone penetrometer for liquid limit determination. The test method devised by Casagrande has been superseded in many parts of the world by the cone penetrometer.

The calibration of the equipment, the mechanical adjustments, and test procedures involved in the Casagrande method may give rise to significant variations in the test results obtained by different operators using the same piece of equipment. In comparison, the cone penetrometer offers considerable advantages over the Casagrande apparatus, it is easier to perform the test, the results are not so dependent on the design of the apparatus, it is applicable to a wide range of soils, and it gives a greater degree of precision between different operators.

The intent of this study is to investigate the possibility of substituting the cone penetrometer for the Casagrande apparatus and to establish appropriate factors for use in conjunction with the one-point method to determine the liquid limit of soils found in Ontario. Recommendations are made with respect to adoption of the cone penetrometer method and suitable factors for obtaining liquid limit by the one-point method.

The use of Atterberg limits, especially liquid limit and plasticity index, in geotechnical engineering design and construction are covered in Chapter 2. Chapter 3 describes the Casagrande and cone penetrometer test methods, including the apparatus and test procedures. The results from studies done by other agencies to compare both methods are also included in Chapter 3. The test data and analyses from this study are provided in Chapters 4 and 5. The test results of each sample used in this study are presented in the form of logarithmic plots in Appendices A and B.

1. Introduction

In geotechnical engineering practice, the liquid and plastic limits (Atterberg limits) are directly used in specifications, semi-empirical methods of design, preliminary estimate of consolidation characteristics and soil classification systems. A soil classification system or the correlation between indices and engineering properties loses its value if the index tests such as liquid limit become more complicated than the test to measure directly the fundamental property needed. For these reasons, the apparatus used for determination of liquid limit must be simple and easy to operate, variations in results obtained by different operators minimised, and the derived parameters based on engineering principles rather than an empirical approach.

The liquid limit apparatus and the test method devised by Casagrande in 1932, was for over 40 years the universally recognised standard method for the determination of liquid limit of clayey soils. This has been superseded in most of the European and Asian countries by the Cone Penetrometer method, and the Casagrande procedure is retained as a subsidiary method. However, in North America, the Casagrande test procedure (ASTM D 4318 and AASHTO T 89) has continued to be the only acceptable method to determine the liquid limit of clayey soils.

Since the introduction of apparatus in 1932, Casagrande worked to standardise the test, and developed the liquid limit device so that the test became more independent of the operator (Casagrande, 1958). The device has been further improved by fitting a drive motor designed to turn the cam at the correct speed, and a revolution counter to count the number of blows required to close the groove.

In spite of the standardisation and refinements to the apparatus, various facets of the equipment and the test procedures can give rise to significant variations in test results between different operators using similar pieces of equipment. Results obtained by the cone penetrometer method have been proved to be more consistent, and less liable to experimental errors, than those obtained by the Casagrande Method.

In 1981, a limited study was completed by the Soils and Aggregates Section of the Ministry of Transportation (Hanks, 1981), on the use of the cone penetrometer as an alternate method to determine the liquid limit of clayey soils. In this study, cones that were developed in USSR (Vasilev in 1949), India (Uppal and Aggrawal in 1953), and Georgia, USA (in 1953), a cone conforming to British Standard BS 1377: 1975, and two types of cones fabricated in our maintenance shop were used. This report recommended that consideration be given to the adoption of the cone penetrometer method as an alternate to the Casagrande procedure described in MTO Test Method LS-703. However, a type of cone penetrometer that results in a liquid limit value similar to the one determined by ASTM D 4318 test procedure, which replaced ASTM D 423, was not recommended. The study also did not establish a relationship between the liquid limit results obtained by the Casagrande and cone penetrometer methods.

The one-point method of liquid limit determination is used as a rapid test procedure when a result of lesser accuracy is acceptable. The liquid limit determination by the one-point method requires the slope angle (factor) of the flow line, which depends on the type of soil and its geologic origin. At present, MTO uses the slope angle or factor that was established by ASTM for soils found in the United States.

This report presents the results of a study undertaken to investigate the possibility of substituting the cone penetrometer conforming to BS 1377:Part 2:1990 for the Casagrande apparatus. The test data from this study were also analysed to verify whether the slope angle of the flow line or the factor that is being used is valid for soils found in Ontario. In addition, the report recommends slope angles for inorganic clays found in Ontario as well as factors for obtaining the liquid limit by the one-point method employing both Casagrande apparatus and cone penetrometer.

2. Engineering Use of Atterberg Limits

2.1 ATTERBERG LIMITS AND INDICES

The Atterberg limits were developed in the early 1900's by a Swedish soil scientist, A. Atterberg (Atterberg, 1911). After several experiments, Atterberg came to the realisation that at least two parameters were required to define plasticity of clays, i.e., upper and lower limits of plasticity. He was able to define several limits of consistency or behaviour, and develop simple laboratory tests to define these limits. Atterberg defined liquid limit as the lower limit of viscous flow and plastic limit as the lower limit of the plastic state.

The Atterberg limits are based on the concept that a fine-grained or clay soil can exist in any of four states, i.e., solid, semi-solid, plastic and liquid, depending on the water content. The water contents that correspond to the boundaries between the states of consistency are termed shrinkage limit, plastic limit and liquid limit. In geotechnical engineering practice, the liquid limit and plastic limit are used for soils classification purposes, and to correlate with the engineering properties and engineering behaviour of fine-grained soils.

The liquid limit, LL, is the lower limit of viscous flow or of the liquid state. It is defined as the moisture content at which the soil sample changes from plastic to liquid state. A standard mechanical device is used to determine the liquid limit.

The plastic limit, PL, is the lower limit of the plastic state. It is the water content at which the soil begins to crumble when rolled out into a 3 mm diameter thread.

The range of water content within which a soil possesses plasticity is known as the plastic range. The numerical difference between the liquid limit, LL, and plastic limit, PL, is the plasticity index, PI, a measure of the plastic range.

$$PI = LL - PL$$

The water that is present in a natural soil deposit is often compared or scaled with the defined limits or boundaries such as Atterberg limits or engineering response. In this way, a soil sample can be categorised whether it will be likely to behave as a plastic, a brittle solid or even possibly a liquid. The index for scaling the natural water content of a soil sample is the liquidity index, LI, and is defined by the equation below.

$$LI = (W_n - PL)/PI$$

Where W_n is the natural moisture content, PL is the plastic limit and PI is the plasticity index of the soil sample.

To measure fundamental soil properties like permeability, compressibility, and shear strength can be difficult, time consuming and expensive. The Atterberg limits and related indices are very useful for soil identification and classification. The Atterberg limits are often used directly in specification for controlling soil for use in earth fill and in semi-empirical methods of design. The Atterberg limits work empirically, i.e., they correlate with engineering properties and behaviour of fine-grained soils. Both the Atterberg limits and the engineering properties are affected by the clay minerals, the ions in the pore water, and the stress history of the soil deposit.

2.2 PLASTICITY CHART AND SOIL CLASSIFICATION SYSTEM

2.2.1 Plasticity Chart

Many properties of clay and silt, such as their dry strength, compressibility, reaction to the shaking test, and consistency near the plastic limit have been correlated based on local experiences with the Atterberg limits by means of the plasticity chart. In this chart, the ordinate represents the plasticity index, PI, and the abscissa the corresponding liquid limit, LL, as shown in Figure 2.1.

The A-line shown in Figure 2.1 generally separates the more clay like materials from those that are silty and also the organic from the inorganic (Casagrande, 1948 and Howard, 1977). The organic clays plot below the A-line, behave in a similar manner to the soils of low plasticity. The silt, clay and organic fractions are further subdivided on the basis of relatively low (L), medium (I) or high (H) liquid limits. The soils that plot in approximately the same area on the plasticity chart tend to have similar engineering behaviour.

The U-line shown in Figure 2.1 indicates the upper range of plasticity index and liquid limit thus far for natural soils (Holtz and Kovacs, 1981). The liquid limit of any soil plot to the left of the U-line, or above the U-line should be retested. The plasticity chart can be used to identify qualitatively the predominant clay mineral in a soil sample.

2.2.2 Soil Classification System

In many soils engineering problems, such as pavement design, empirical or semi-empirical methods are employed. There are no rational mathematical models or expressions available for an analytical solution. For these reasons, soils are sorted into groups showing similar behaviour. The most commonly used characteristics in the soil classification systems are particle size and Atterberg limits.

The correlation of engineering or physical behaviour with a soil group in a soil classification

system is usually an empirical one developed through considerable experience. The soil classification system provides a systematic method of categorising soils according to their probable engineering behaviour, and allows engineers access to the accumulated experience of others.

The widely used Unified Soil Classification System (USCS) and AASHTO system employ very simple index type tests to obtain the characteristics of the soil needed to place it in a given group.

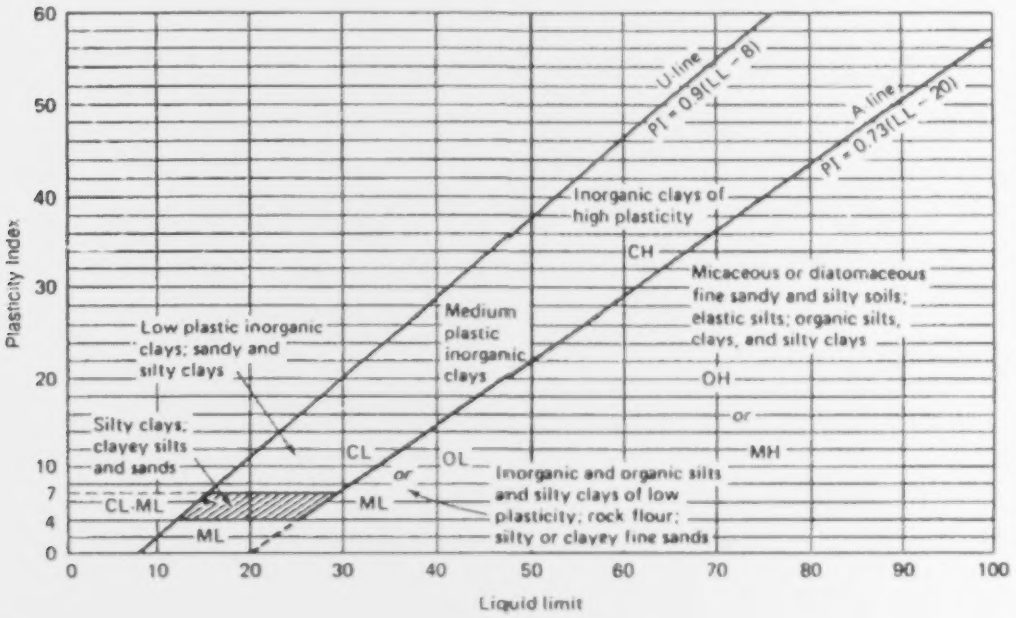

Figure 2.1 Plasticity Chart Showing Several Representative Soil Types (Holtz & Kovacs, 1981)

2.3 IDENTIFICATION OF CLAY MINERALS USING ATTERBERG LIMITS

Techniques such as x-ray diffraction, differential thermal analysis (DTA) or electron microscopy are often used to identify clay minerals. A detailed quantitative analysis by these processes may not be easy with soils, which are mixtures of clay and other minerals and organic constituents.

The plasticity chart can also provide information as useful, at least from an engineering point of view, as the more sophisticated diffraction and DTA analyses. The approach is based on the concept that the Atterberg limits for the soils are related to the amount of water that is attracted or adsorbed on the surface of the soil particles. The amount of adsorbed water will be largely

influenced by the amount and type of clay that is present in the soil. On the basis of this reasoning, Skempton (1953) defined a quantity called activity, A, to correlate plasticity index and percentage of clay.

$$A = (PI) / (\% \text{ of Clay})$$

Figure 2.2a shows the relationship between plasticity index, PI, and clay fraction obtained on prepared mixtures of various percentages of clay particles. Figure 2.2b shows the activity values obtained by Skempton (1953) for all three basic clay minerals, i.e., Kaolinite, Illite and Montmorillonite.

A second approach to determine the predominant clay mineral in a soil sample is to simply locate the sample on the LL-PI chart shown in Figure 2.3 and compares its location with those of known minerals. The glacial lake clays from around the Great Lakes region in the United States and Canada are predominantly illite, and plot immediately above the A-line.

2.4 APPROXIMATE METHOD TO ESTIMATE COMPRESSION INDEX

The consolidation test to determine the compression index and coefficient of consolidation involves considerable time and expense. Because of this, it is sometimes desirable to relate the compression index to the simple classification properties of soils. These relationships are also commonly used for preliminary designs and estimates, and for checking the validity of test results.

Terzaghi and Peck (1967) recommended the equations given below based on their research on undisturbed clays of low to medium sensitivity.

$$C_C = 0.009(LL - 10)$$
$$C_C = 1.3\ C'_C$$

Where C_C corresponds to the field consolidation line in the void ratio, e, versus Log σ plot, and C'_C is the compression index for the clay in its remoulded state.

The scatter of the real values of C_C from those determined by the above equations is about $\pm$ 30 % (Skempton, 1944). These equations are widely used, despite their wide reliability range, to make initial consolidation settlement estimates. The equations given above should not be used if the sensitivity of the clay is greater than 4, the liquid limit is greater than 100 or the clay contains a high percentage of organic matter.

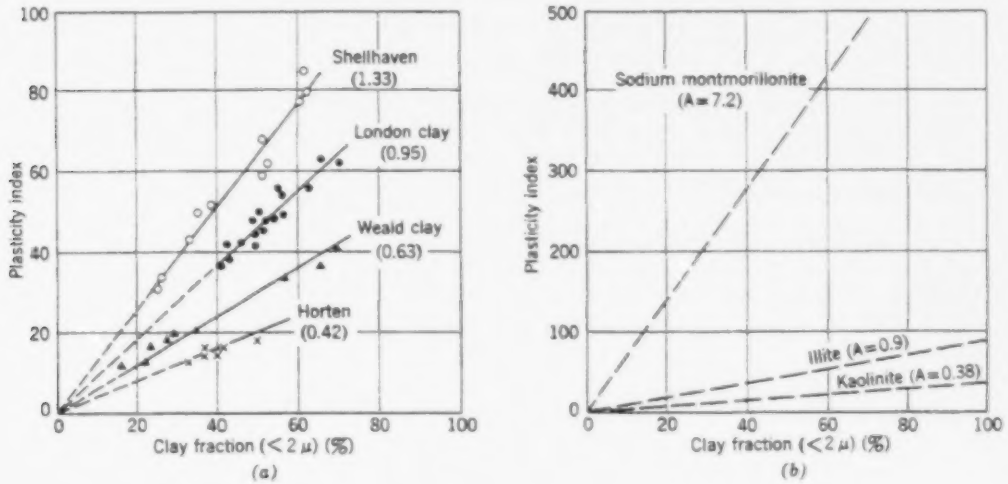

Figure 2.2 Relation between Plasticity Index and Clay Fraction (Lambe & Whitman, 1979)

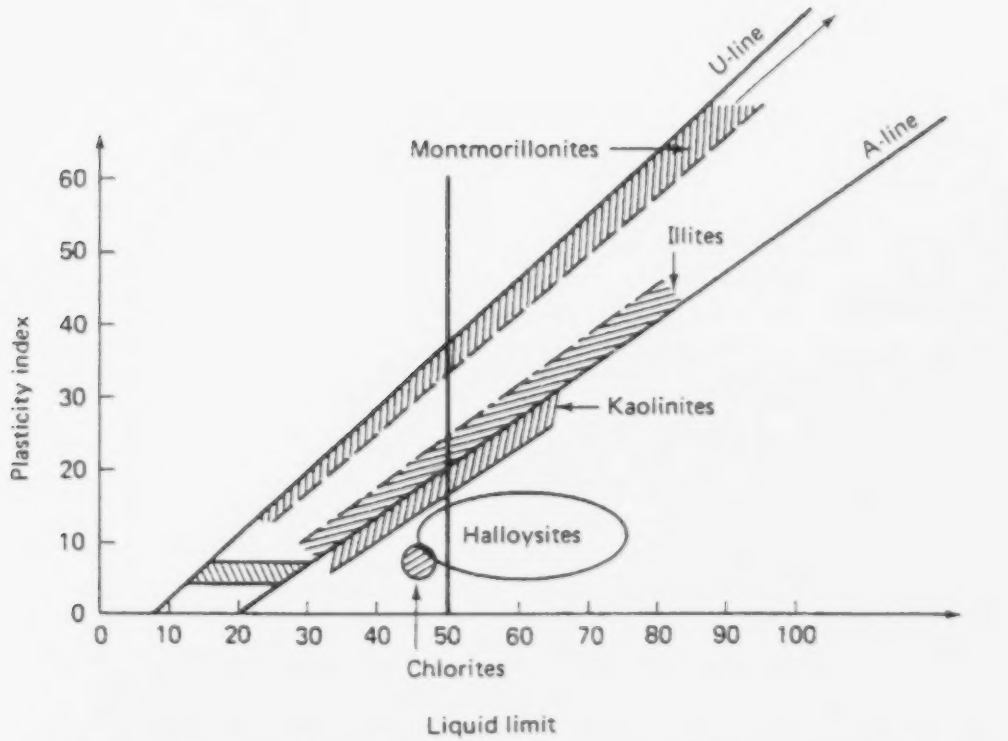

Figure 2.3 Location of Common Clay Minerals on Plasticity Chart

Figure 2.4 shows the relationship between liquid limit and compression index, C'_C, for remoulded clays (Skempton, 1944). The results shown in Figure 2.4 are from the test performed on samples selected at random. These samples were selected from different parts of the world, and the assortment included both ordinary and extra sensitive clays.

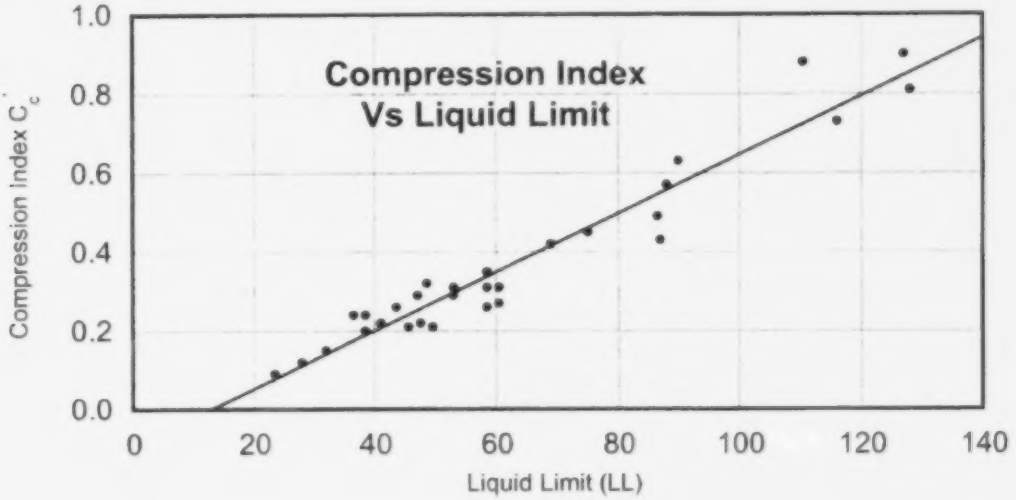

Figure 2.4 Relationship between Liquid Limit and Compression Index for Remoulded Clays (Skempton, 1944)

2.5 STRESS-STRAIN RESPONSE AND ESTIMATION OF SHEAR STRENGTH

The liquidity index, LI, is indicative of the behaviour and stress-strain response of a natural soil deposit when it is sheared under unconfined compression or by a vane shear apparatus. The water content continuum of a clayey soil in its various states and its stress-strain response when sheared are shown in Figure 2.5.

It has been found by Skempton (1953 & 1957) and Bjerrum (1954) that the ratio between the undrained shear strength, C_U, of normally consolidated or loaded natural deposits, and the effective over burden pressure, P', at the depth corresponding to the shear strength test is a constant. The ratio designated as C_U/P' is a constant for sedimentary clays provided that the plasticity index is approximately the same throughout the depth. A correlation between the C_U/P' ratio and the plasticity index for various deposits or fairly homogeneous portions of deposits is shown in Figure 2.6.

Figure 2.6 makes possible a rough evaluation of the undrained shear strength, as determined by means of unconfined compression or vane shear tests of normally loaded deposits on the basis of the results of Atterberg limit tests.

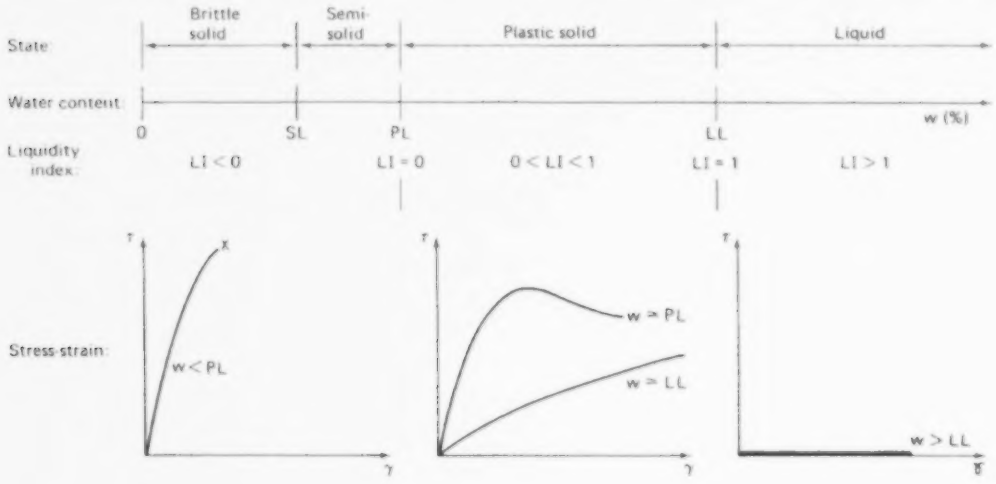

Figure 2.5 Generalised Stress-Strain Response at Various States of a Clay Soil (Holtz & Kovacs, 1981)

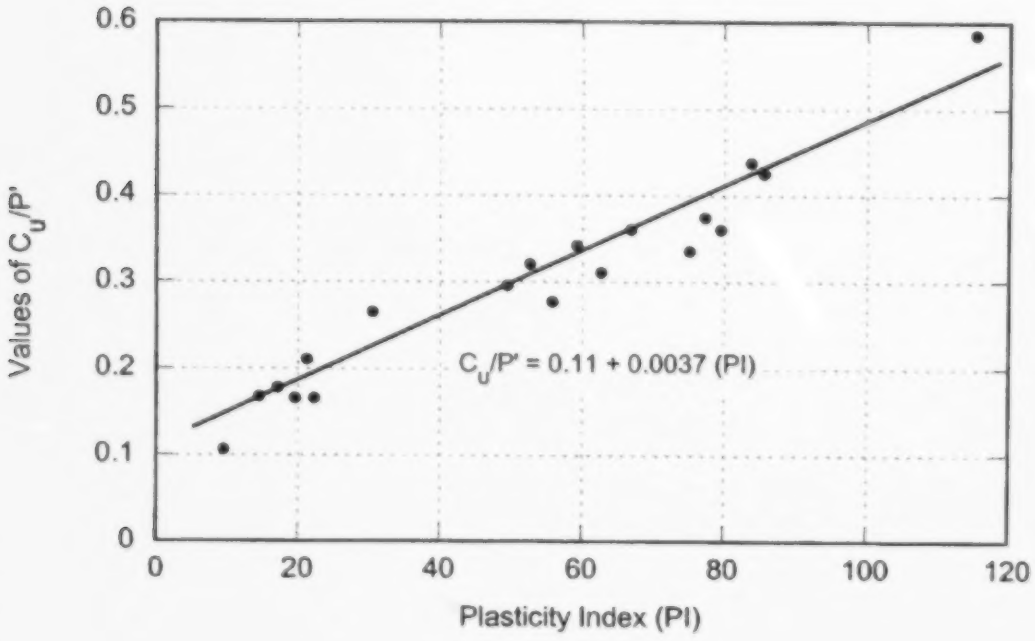

Figure 2.6 Statistical Relation between C_U/P' Ratio and Plasticity Index (Terzaghi & Peck, 1967)

2.6 LIMITATION OF EMPIRICAL CORRELATIONS

One must realise that all of the limits and indices discussed above are determined on soils that have been thoroughly mixed and remoulded into test samples. The limits therefore give no indication of particle fabric or residual bonds between particles, which may have been developed in the natural soil but are destroyed in preparing the specimen for the determination of liquid limit .

The natural structure of a soil deposit very strongly governs the engineering behaviour and properties. It is emphasised that the empirical correlations given or discussed above do not eliminate the need for detailed soil investigations or for testing engineering properties. The Atterberg limit tests inherently involves disturbance of the soil samples. The liquid and plastic limits may not give a good indication of the behaviour of the in-situ or undisturbed soil.

3. Description of Test Methods

3.1 HISTORIC BACKGROUND

Consistency limits originally developed by Atterberg were rather arbitrary and not easily reproducible, even by experienced operators. The tests were standardised by Casagrande, and the liquid limit device developed by him was recognised universally and continues to be accepted in North America as the only method to determine the liquid limit of clayey soils.

The liquid limit test as devised by Casagrande has many shortcomings. Problems with the Casagrande apparatus resulted in the development of cone penetrometers for liquid limit determination. In 1975, the British Standards Institution introduced the cone penetrometer as the preferred method of determining the liquid limit of soils.

3.2 CASAGRANDE METHOD (ASTM D 4318)

Casagrande defined the liquid limit as the water content at which a standard groove cut in a remoulded soil sample placed in a metal cup will close over a distance of 13 mm at 25 blows of the cup falling 10 mm on a hard rubber or micarta plastic base. Complete details of the Casagrande apparatus and test procedures are given in the Annual Books of ASTM Standards.

3.2.1 Apparatus

The liquid limit device shown in Figure 3.1 consists of a brass cup suspended from a carriage designed to control its drop onto the base. The principle of its action is shown in Figure 3.2. The device may be fitted with a revolution counter and operated by either a hand crank or electric motor. The cup must fall freely without too much side play and the height to which the cup is lifted must be 10 ± 0.2 mm above the base. The spacer gauge to check the height of drop and the grooving tool are shown in Figure 3.3. Some of the shortcomings that are associated with the Casagrande test method are as follows:

- The difficulty of cutting a groove in some soils, particularly those containing sand or silt;
- Tendency of soils of low plasticity (LL < 35) to slide in the cup or liquefy with shock rather than to flow plastically;
- Sensitivity to small differences in apparatus, such as hardness of the base, shape of the cam, and wear of the cup; and
- Sensitivity to operator technique resulting from shape and alignment of groove, rate of revolution of the handle or speed of operation, and observation of point of groove closing.

3.2.2 Sample Preparation

In both Casagrande and cone penetrometer methods, tests are carried out on remoulded soil passing a 425 μm sieve. The ASTM test method does not specify a preferred or definitive sample preparation procedure, but permits performing the test on samples prepared by three methods. The methods include testing a soil sample in its natural state, i.e., at natural moisture content, or testing a sample following a wet or dry sieving process to remove the particles retained on a 425 μm sieve. However, the test method requires that the method of preparation of a soil sample always be reported along with the test results.

Wherever possible, the soil used for Atterberg limits tests should not be dried before testing. Even air-drying at laboratory temperature can cause irreversible changes in the physical behaviour of some soils.

When the soil consists of clay and silt with little or no material retained on a 425 μm sieve, the sample can be prepared for testing from its natural state. A soil that includes particles retained on a 425 μm sieve is prepared by adding distilled or de-ionised water to a representative sample at its natural moisture content and washing through a 425 μm sieve. Samples for the dry preparation method are dried at room temperature or in an oven at a temperature not exceeding 60° C, and sieved through a 425 μm sieve after breaking down aggregations of particles in a mortar using a rubber pestle. Air or oven dried samples for the tests are prepared by adding distilled or de-ionised water and leaving overnight to reach moisture equilibrium and to obtain a uniform distribution of water throughout the sample.

3.2.3 Test Procedure

Prior to commencing the test, the apparatus is checked for its cleanness, free movement of the cup without too much side play, and that the height of drop is 10 ± 0.2 mm. The soil sample that was thoroughly mixed with distilled or de-ionised water followed by proper maturing is placed in the cup by pressing it from the middle outwards to prevent any trapping of air underneath. The surface of the soil paste is smoothed off level and parallel to the base, giving a depth of 10 mm at its deepest point as shown in Figure 3.4a.

A groove is cut through the sample from back to front, dividing it into two halves. The direction and position of the grooving tool while cutting the groove are shown in Figure 3.4b. The completed groove is shown in Figure 3.5.

The crank handle of the device is turned at a steady rate of two revolutions per second, so that the cup is lifted to 10 ± 0.2 mm high and dropped. The handle is turned continuously until the groove is closed along a distance of 13 mm, and the number of blows required to close the groove is recorded.

A slice of soil approximately the width of the spatula, extending from edge to edge of the soil cake at right angles to the groove and including that portion of the groove in which the soil

flowed together, is taken and placed in a moisture content container of known mass. The moisture content of this portion of the soil is determined as in the moisture content test by drying at 110 ± 5^{o} C. The test is repeated three to four times by adjusting the water content of the soil sample such that the number of blows is roughly evenly spaced over the range from 15 to 35. A soil of higher moisture content will normally require fewer drops to close the groove.

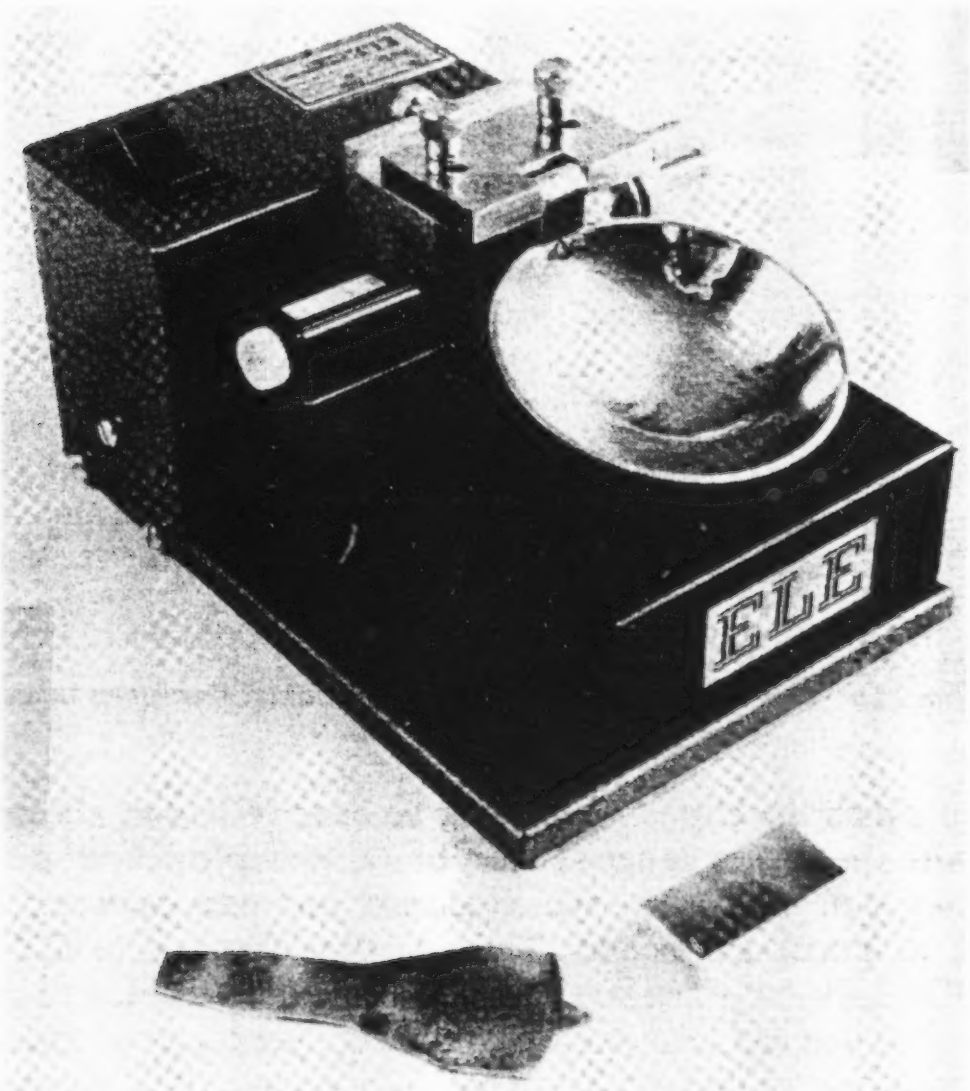

Figure 3.1 Casagrande Liquid Limit Apparatus and Grooving Tool

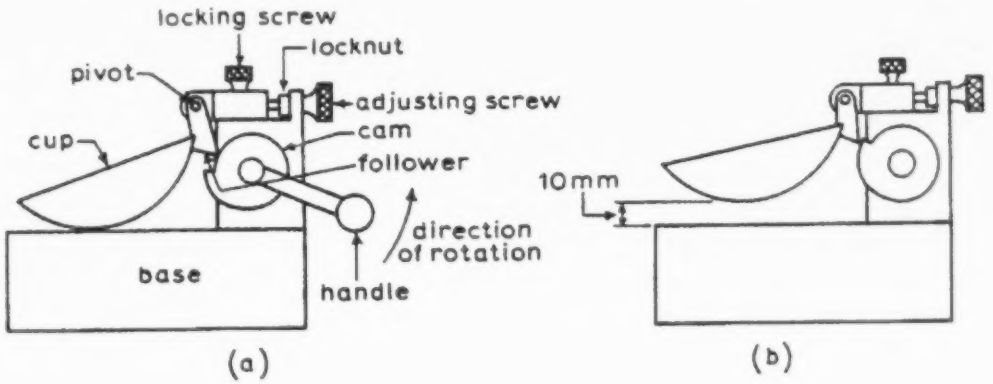

Figure 3.2 Principle of Casagrande Apparatus

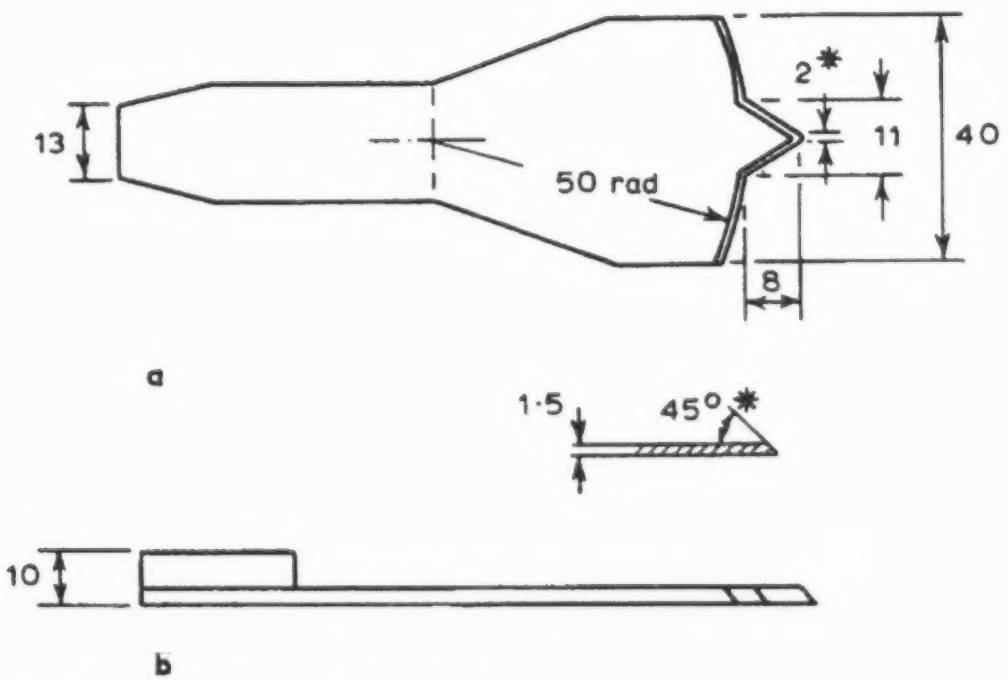

Figure 3.3 Grooving Tool and Spacer Gauge (dimensions in mm)

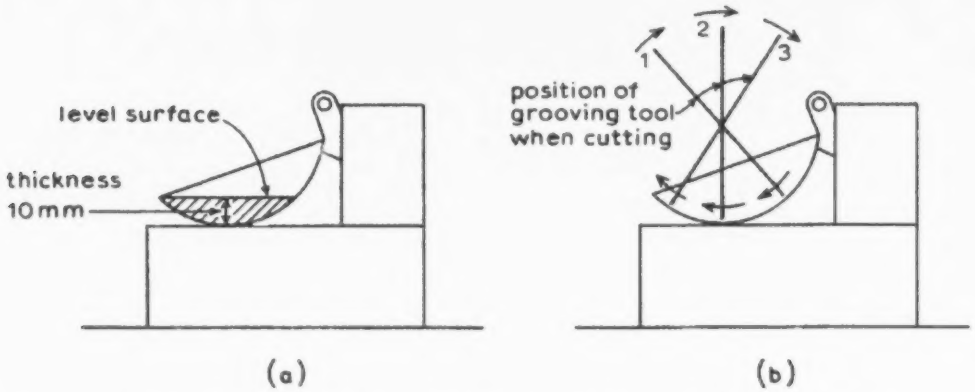

Figure 3.4 Soil Placed in Cup and Use of Grooving Tool

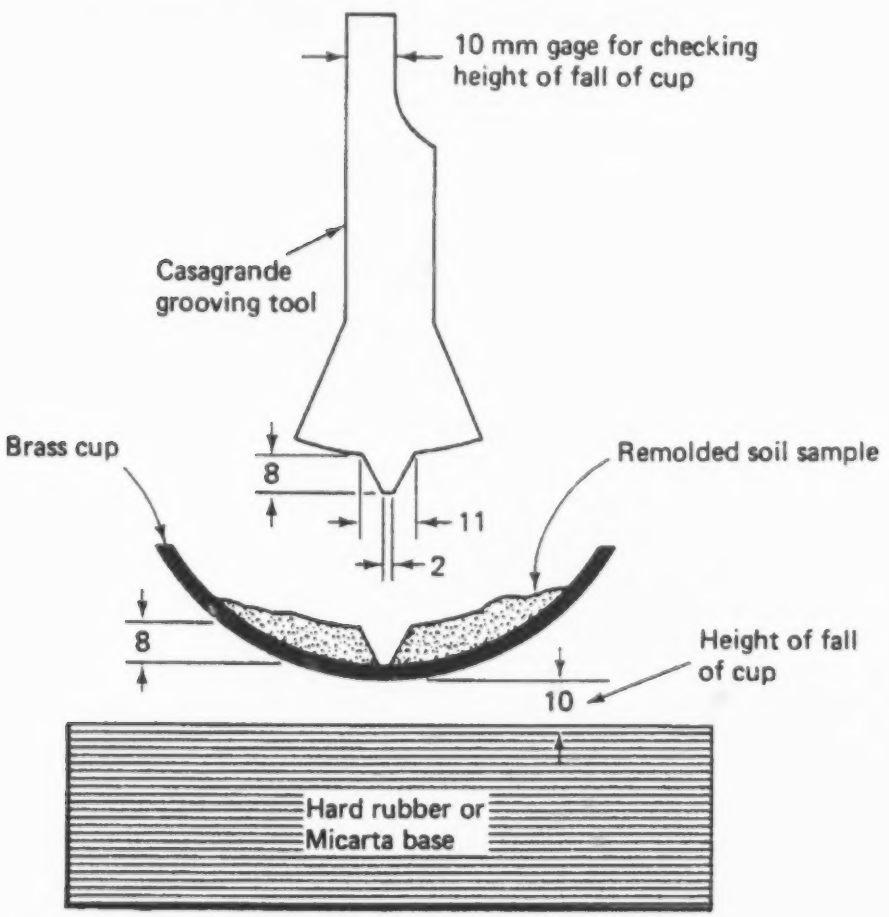

Figure 3.5 Schematic Diagram of Completed Groove

3.2.4 Calculations

The moisture content for each blow count is calculated as in the moisture content test. A graph using the semi-logarithmic chart is plotted with moisture content as ordinate (linear scale) against the corresponding number of blows as abscissa (logarithmic scale). The best straight line fitting the plotted points is drawn. This line is called the 'flow curve' as shown in Figure 3.6.

The moisture content corresponding to 25 blows is read from the flow curve and recorded to the nearest 0.1 %. The moisture content read off from the flow curve is reported to the nearest whole number as the liquid limit.

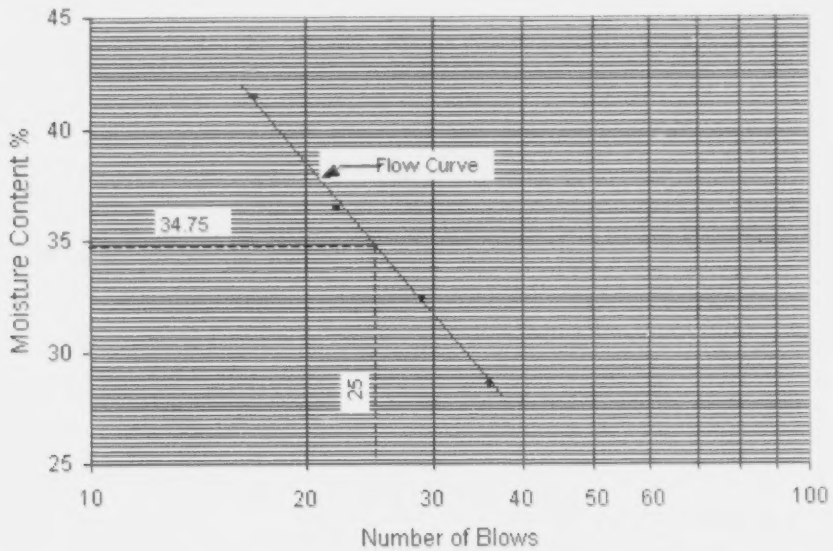

Figure 3.6 Plot of Moisture Content VS Number of Blows

3.3 CONE PENETROMETER METHOD

3.3.1 Historic and Theoretical Background

In 1915, John Olson introduced the fall cone method (Geonor, 1962) to measure the undrained shear strength of sensitive clays. This method was introduced for the Geotechnical Commission of the Swedish State Railways. The equipment was originally designed for classifying soils.

The test method assumes that the shear strength of soil at constant penetration of a cone is directly proportional to the mass of the cone. The relationship between shear strength S_u of soil and the depth of penetration D of a cone of known mass M is given by (Hansbo, 1957) the equation:

$$S_u = k\,(M/D^2)$$

Where k is a constant, which depends mainly on the cone angle, but is also influenced by the sensitivity of clay.

The relationship between shear strength and depth of penetration of a cone into the soil was the basis for the development of the cone penetrometer method to determine the liquid limit of clayey soils. The definition of the liquid limit in this method is dependent on the point at which the soil begins to acquire a shear strength value of about 1.7 kN/m^2. Therefore, the liquid limit in this method is based on the measurement of penetration into the soil of a standardised cone of specified mass and cone angle.

British Standard 1377 was developed at Transportation Road Research Laboratory (TRRL) from various cone tests, which have been in use in other countries, and was adopted by the British Standards Institution in 1968 with a few modifications. The cone penetrometer was accepted as the preferred British Standard method in 1975 for determination of the liquid limit of clayey soils. The liquid limit in this method is defined as the moisture content corresponding to a cone penetration depth of 20 mm into the soil.

3.3.2 Cone Specifications from Various Countries

The mass and cone angle of standard cones that are being used in various countries to determine the liquid limit varies widely. The mass of cone specified by various standards range from as low as 60 grams (Swedish cone) to as high as 148 grams (Indian cone). The cone angle that is being used or specified in various countries ranges from 30° (British cone) to 60° (Swedish cone). The depth of penetration at the liquid limit is influenced by mass of the cone and cone angle. The depth of penetration required by various specifications ranges from 10 mm to as high as 25 mm. The variation in cone specification as developed or used in various countries is shown in Table 3.1

3.3.3 Factors Affecting the Reproducibility

The sharpness and surface texture of the cone may influence the liquid limit results. Sherwood (1968) concluded that the sharpness of the cone does influence the results, but the effect is not very large. He also indicated that the bluntness of the cone would become visually apparent before it reaches the stage where it has any significant effect on the results. The cones are not expensive to replace and the rate of wear of a stainless steel or aluminium cone is generally very small.

Sherwood (1968) also concluded that the effect of surface texture was very small and the effect on the liquid limit was within the limits of reproducibility. The report also recommends that the effect of surface texture could be discounted for practical purposes.

Table 3.1 Cone Specifications from Various Countries

Country & Date	Cone Angle	Length mm	Material Type	Mass g	Cup Dimensions, mm		Penetration at LL, mm
					Diameter	Depth	
USSR 1949	30	25.0	Brass	76	37	20	10
India 1953	31	30.48	Metallic	148	50	50	25
Georgia (USA) 1951	30	20.0	Stainless Steel	75	40	20	10
Britain 1975	30	35.0	Stainless Steel or Duralumin	80	55	40	10
France 1966	30	35.0		80	55	35	20
Sweden 1922	60			60			10

3.4 BRITISH STANDARD CONE PENETROMETER (BS 1377: Part 2: 1990)

3.4.1 Apparatus

The test method requires the same apparatus as is used for bituminous materials testing (BS2000: Part 49) but fitted with a special cone. The penetrometer apparatus complying with the test requirements is shown in Figure 3.7, and the details are illustrated in Figure 3.8a. The cone for the penetrometer is made of stainless steel or duralumin with a smooth, polished surface. The cone is approximately 35 mm long with a cone angle of 30° and sharp point. The mass of the cone including the sliding shaft is 80 ± 0.1 grams. The sharpness gauge to check the point of the cone is shown in Figure 3.8b. This consists of a small steel plate 1.75 ± 0.1 mm thick with a 1.5 ± 0.02 mm hole accurately drilled and reamed. The apparatus also includes a metal cup, of brass or aluminium alloy, 55 mm in diameter and 40 mm in depth. The rim of the cup must be parallel to the flat base.

3.4.2 Sample Preparation

Sample preparation is similar to that described in Section 3.2.2 for the Casagrande method. However, BS 1377: 1990 requires that the soil should not be allowed to become dry for the definitive methods of testing. This standard specifies the use of soil in its natural state where possible, or a wet preparation procedure for removal of particles retained on the 425 μm sieve.

3.4.3 Test Procedure

The cone is the most important part of the apparatus. Prior to each test, it is checked for its mass, sharpness of the point, and free fall when the release button is pushed. The soil sample that has been matured by mixing with distilled or de-ionised water followed by thorough mixing and kneading is placed in the cup by pressing the soil paste against the side and bottom of the cup to avoid trapping of air. The top surface of the soil paste is finally smoothed off level with the rim of the cup using a straight edge.

The cone and shaft unit is locked near the upper end of its travel and the supporting assembly is carefully lowered so that the tip of the cone is within a few millimetres of the surface of the soil in the cup. The height of the cone is adjusted by holding it and pressing the release button so that the tip just touches the soil surface. The dial gauge to measure the depth of penetration is lowered to make contact with the top of the cone shaft, and the initial reading is recorded.

The cone is allowed to fall freely by pressing the release button and held in the pressed position for 5 seconds by timing with a timer. In the case of a cone penetrometer fitted with an auto-timer, the release button is pressed and released immediately, and the re-locking of the stem after 5 seconds is indicated by a click noise.

After 5 seconds the cone is locked in place and the dial gauge stem is lowered to make contact with the top of the cone shaft. The dial gauge reading is recorded to the nearest 0.1 mm. The difference between the initial and final dial gauge reading is the depth of penetration into the soil, and is recorded to the nearest 0.1 mm. The test is repeated by adding a little more wet soil to the cup, without entrapping air, and smoothing off, until the overall differences among three consecutive trials are within 1 mm. The average of three penetrations is recorded and the sample is taken for moisture content determination.

Approximately 10 grams of sample from the area penetrated by the cone are taken using a small spatula and placed in a moisture content container of known mass. The moisture content of this portion of the soil is determined as in the moisture content test by drying at $110 \pm 5^{\circ}$ C. The test is repeated four times by adjusting the water content of the sample so that the penetration values are evenly spaced over the range of 15 mm to 25 mm.

3.4.4 Calculations

The moisture content of the soil sample corresponding to each penetration reading is calculated as in the moisture content test. A graph using the linear scale is plotted with moisture content as abscissa and depth of penetration as ordinate. The best straight line fitting the plotted points is drawn. A typical graph is shown in Figure 3.9.

The moisture content corresponding to a cone penetration value of 20 mm is read off to the nearest 0.1 %. The result is reported to the nearest whole number as the liquid limit.

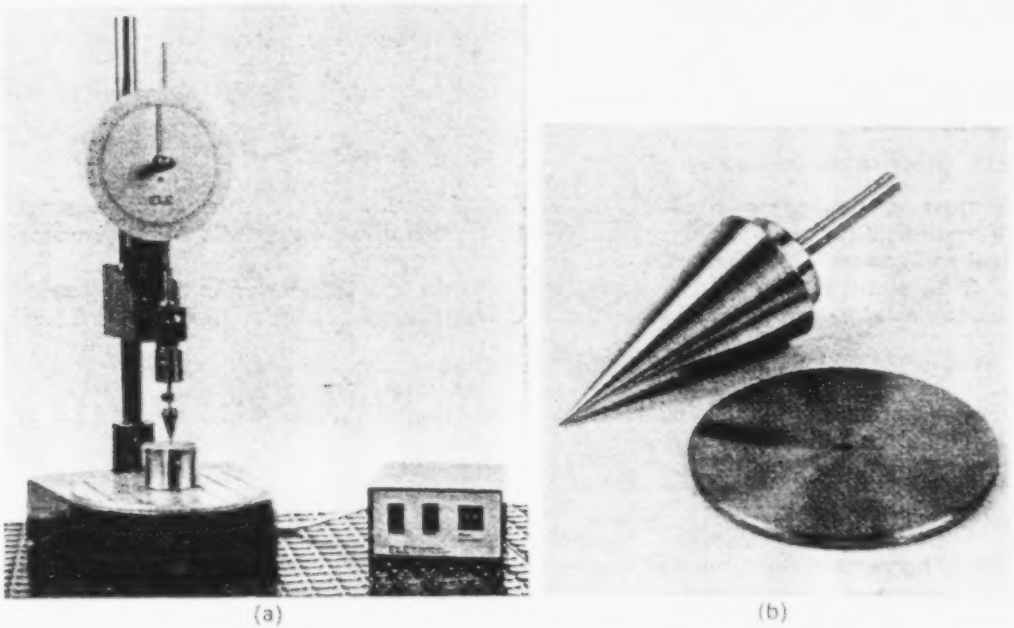

Figure 3.7 Apparatus for Cone Penetrometer Test Method

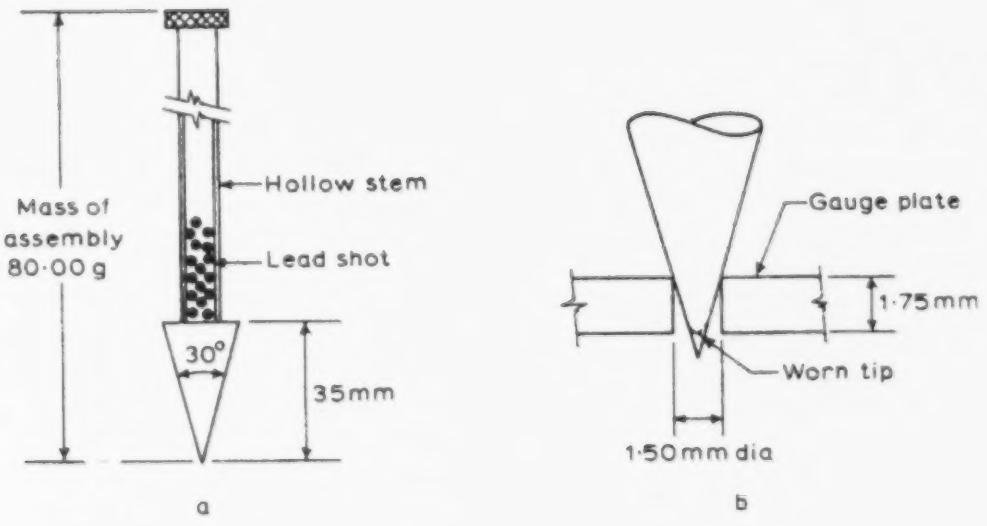

Figure 3.8 Details of Cone and Gauge Plate

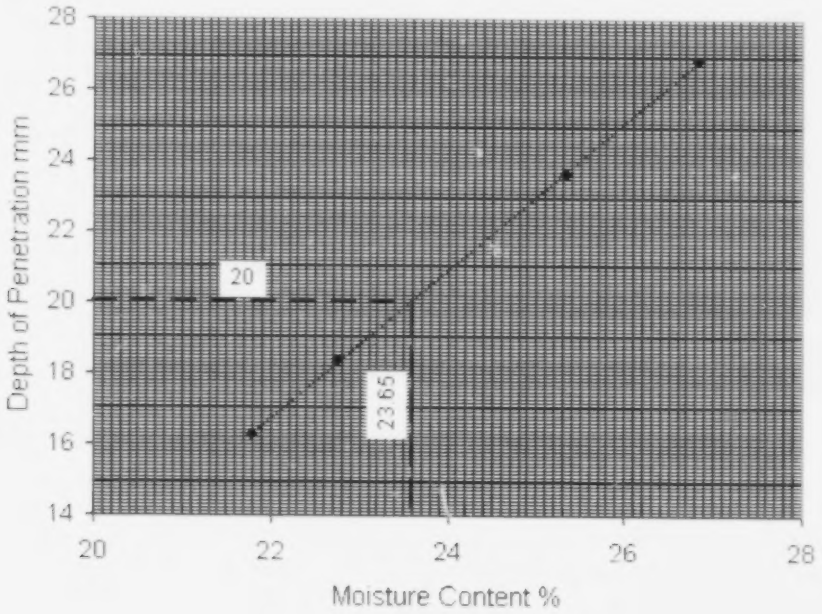

Figure 3.9 Plot of Moisture Content VS Depth of Penetration

3.5 COMPARISON OF CASAGRANDE AND CONE PENETROMETER METHODS

3.5.1 Comparison of Liquid Limit Results by Both Methods

In both methods, the fraction of the soil passing a 425 μm sieve is used, and the test is carried out on remoulded samples. The cone penetrometer method, compared to the Casagrande procedure, may not be any quicker to perform, but it is fundamentally more satisfactory, because the mechanics of the test depend directly on the static shear strength of the remoulded soil. The Casagrande test procedure, on the other hand, introduces a dynamic component, which is not related to shear strength. A summary table comparing both methods is provided in Table 3.5.

The shear strength at the liquid limit by both Casagrande and cone methods has been determined at the Swedish Geotechnical Institute (Karlsson, 1977) by means of a laboratory vane. The results from his study indicate that the shear strength at the liquid limit by the Casagrande method varied considerably, from about 0.5 kPa for Bentonite, to 1 kPa to 2 kPa for Illite and Kaolinite. However, the shear strength at the liquid limit by the cone method was about 1.7 kPa for all the samples. The study concluded that the variation in shear strength at the liquid limit by the Casagrande method depends not only on the shear strength itself, but also on the density of the soil sample.

The studies carried out by Sherwood (1968) and Littleton (1977) indicate that there is little or no difference between the results obtained by each method for liquid limit values up to 100. However, above 100, the cone method tends to give values slightly lower than the values obtained by the Casagrande method (Littleton, 1977). The relationship between results obtained by the Casagrande and cone methods, based on the evidence available to date, is shown in Figure 3.12 (Head, 1992).

3.5.2 Effect of Operator Technique on Precision

A study was conducted by TRRL (Sherwood, 1968) to review the methods that were in use for the determination of the liquid limit of soils by cone penetrometers. In this study, experiments were made to find out whether the cone penetrometer could give more consistent values than the Casagrande method. To study the effect of operator technique on the reproducibility of the results, eight operators were employed to perform the tests on soils ranging from low to high plastic clays. The tests were performed by both cone penetrometer and Casagrande methods. The operators employed were all experienced with the Casagrande method but with the exception of one (Operator A), none had used the cone penetrometer before. The results of this study are reproduced in Table 3.2.

The results from this study show that the cone penetrometer method is capable of producing liquid limit results that are much more reproducible than the Casagrande method. This study also concluded that the cone penetrometer test offers considerable advantages over the Casagrande apparatus, in that it is easier to perform the test, the results are not so dependent on the design of the apparatus or the manner in which it is used, and it is applicable to a wide range of soils. The findings from the study by TRRL suggest that the results obtained by the cone penetrometer method are more consistent, and less liable to experimental and operator errors, than obtained by the Casagrande procedure.

Table 3.2 Results of Liquid Limit Determined by Casagrande Apparatus and Cone Penetrometer from Sherwood, 1968

Operator	LL by Casgrande Apparatus			LL by Cone Penetrometer		
	Soil No. 2	Soil No. 9	Soil No. 11	Soil No. 2	Soil No. 9	Soil No. 11
A	32.0	63.8	73.8	35.5	65.5	73.3
B	30.1	67.4	73.2	33.4	64.8	73.4
C	35.2	66.6	75.7	35.7	64.8	75.8
D	37.0	67.7	76.4	36.9	64.4	73.6
E	38.1	69.8	76.8	35.9	66.2	73.2
F	35.4	68.7	75.5	36.7	65.6	73.1
G	36.5	70.2	76.1	37.4	65.9	72.6
H	38.0	69.1	76.3	37.0	66.0	73.4
Mean	35.3	67.9	75.5	36.1	65.4	73.5
Stdn.	2.67	1.98	1.22	1.20	0.61	0.89
C.O.V	7.50	2.80	1.60	3.30	0.93	1.20

3.5.3 Results from MTO Proficiency Sample Testing Program

MTO annually conducts a Soils and Aggregates Proficiency Sample Testing program, in order to monitor and improve the quality of testing services provided by the private laboratories. The participating laboratories are asked to perform a number of different tests on pairs of samples that have been prepared and randomly selected by the Soils and Aggregates laboratory.

The soil sample for this proficiency program is air dried over a period of six weeks, powdered past 2.0 mm using a Fritsch Soil Mill Pulveriser, and placed in 50 buckets. Individual scoops from each bucket are then placed in the hopper of a small spinning riffle splitter, which fills 24 identical 2 Kg containers per run. This method is used to create 50 uniform buckets. The 500g correlation materials are obtained from splitting samples from these buckets in the spinning riffler and then randomising for distribution to participating laboratories. This use of a spinning riffler ensured that as far as possible, each sample was identical to every other sample.

The soils used in this proficiency program for last 15 years range from low (LL < 35) to medium (35>LL<50) plastic clays typical of those found in the Province of Ontario. The statistical data gathered since 1989 to date are presented in Table 3.3. In addition, the range of standard deviation obtained through the MTO Proficiency Sample Testing Program over fifteen years is shown in Figures 3.10 and 3.11 in the form of a scatter plot.

There is no certification, accreditation or on-site inspection program in Ontario, other than the voluntary program introduced by MTO in 1999, for laboratories testing soils to participate in. The data that are presented in Table 3.3 represent the common standard in the consulting industry for geotechnical designs and construction. The coefficient of variation (C.O.V.) computed from the mean and standard deviation reported for each year varies from 4.3% to as high as 10.7%, irrespective of the type of clay tested. The results show noticeable improvement since 1999. However, the coefficient of variation is significantly higher than the values reported by Sherwood (1968) for cone penetrometer method and is also higher than the precision estimate recommended by ASTM (Table 3.4) for low plastic (CL) clays.

The results reported by Sherwood (1968) in Table 3.2 indicate a higher coefficient of variation for low plastic clay compared to that for high plastic clay, but this trend is not evident from the MTO proficiency sample results or the precision statement published by ASTM. Investigations in both the United States and Britain (Sherwood, 1968 and ASTM D 4318) have concluded that the results of the liquid limit test obtained with the Casagrande apparatus are liable to vary widely when the test is carried out by different laboratories. The results from the MTO proficiency program also confirm these conclusions.

Table 3.3 MTO Soil Proficiency Sample Results for Liquid Limit Test

Year	No. Of Participants	No. Of Outliers	Sample No.	Statistical Data for Liquid Limit Test Results		
				Mean	Stdn.	C.O.V. (%)
1989	13	0	5.89	22.9	2.46	10.7
			6.89	22.9	2.36	10.3
1990	11	0	5.90	21.6	1.26	5.8
			6.90	21.7	1.38	6.4
1991	8	0	5.91	22.1	1.88	8.5
			6.91	21.8	2.21	10.1
1992	19	0	5.92	21.7	2.19	10.1
			6.92	21.9	1.70	7.8
1993	26	0	5.93	45.7	4.85	10.6
			6.93	44.8	4.36	9.7
1994	35	1	5.94	45.3	4.58	10.1
			6.94	46.0	3.50	7.6
1995	28	0	5.95	29.6	2.45	8.3
			6.95	29.5	2.95	10.0
1996	43	2	5.96	30.0	1.79	6.0
			6.96	30.1	1.62	5.4
1997	67	1	5.97	28.8	2.07	7.2
			6.97	28.9	2.11	7.3
1998	68	4	5.98	36.8	2.04	5.5
			6.98	37.3	2.26	6.1
1999	77	9	5.99	36.9	1.59	4.3
			6.99	36.9	1.62	4.4
2000	74	0	5.00	34.6	2.00	5.8
			6.00	34.6	1.93	5.6
2001	81	7	5.01	27.3	1.18	4.3
			6.01	27.3	1.18	4.3
2002	78	5	5.02	34.1	2.8	8.2
			6.02	27.4	1.6	5.8
2003	78	1	5.03	34.0	2.2	6.5
			6.03	33.8	1.9	5.6

3.5.4 Precision and Bias

ASTM Standard D 4318-00, the latest revision, provides a precision statement based on wet sample preparation and the multi-point method, for judging the acceptability of test results obtained by the Casagrande procedure. The precision estimates published in the ASTM Standard for three soil types are based on the results of twenty-four laboratories, which participated in the inter-laboratory program conducted by the ASTM Reference Soils and Testing Program (RR: D18-1013). Laboratories that participated in this inter laboratory study are either accredited or inspected by AASHTO and ASTM to ensure the quality of testing. The data presented by ASTM represent the standard practice in the design and construction industry in the United States. The precision estimates published by ASTM (latest revision) are provided in Table 3.4.

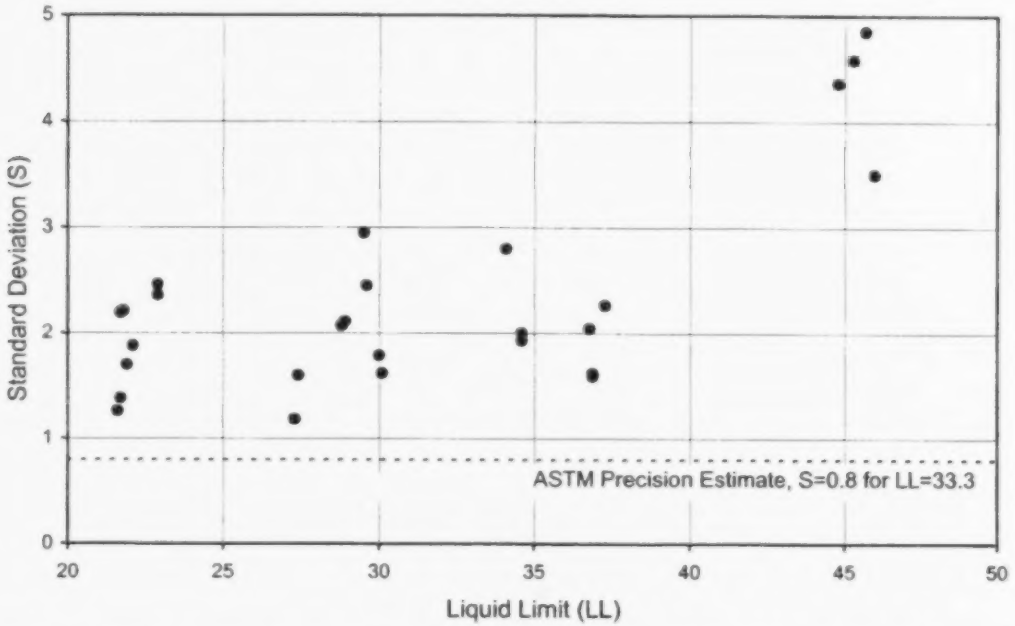

Figure 3.10 Multi-Laboratory Standard Deviation for Liquid Limit from MTO Proficiency Sample Testing Program from 1989 to 2002

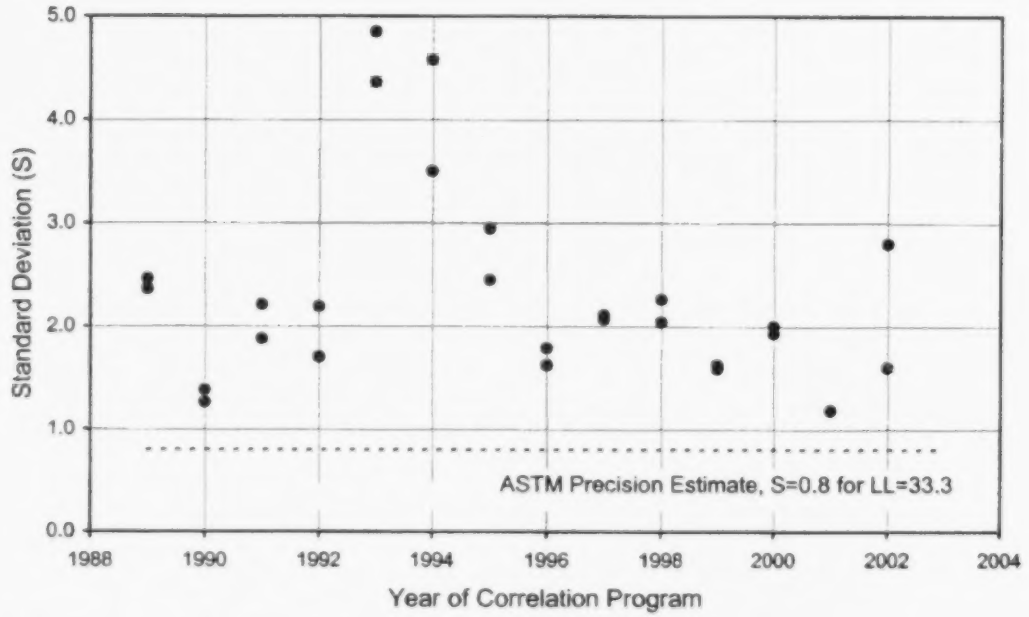

Figure 3.11 Multi-Laboratory Standard Deviation for Liquid Limit from MTO Proficiency Sample Program

An examination of both the precision estimates by ASTM and the values reported by Sherwood (1968) suggests that the results obtained by the cone method are more consistent and reproducible than the results obtained by the Casagrande method. ASTM also cautions the users that the precision estimates may vary with soil types and methods used, and judgment is required when applying these estimates to another soil and method used. ASTM has not published a bias statement because there is no acceptable reference value for this test method.

Table 3.4 ASTM Recommendations for Precision Estimate and Acceptance Criteria

Soil Type	Liquid Limit	Standard Deviation	Acceptable Range	Coefficient of Variation
CH	59.9	2.1	6	3.5
CL	33.3	0.8	2	2.4
ML	27.1	1.3	4	4.8

British Standard BS 1377: Part2: 1990 does not provide a precision and bias statement and assumes that the execution of its provisions is entrusted to appropriately qualified and experienced technicians.

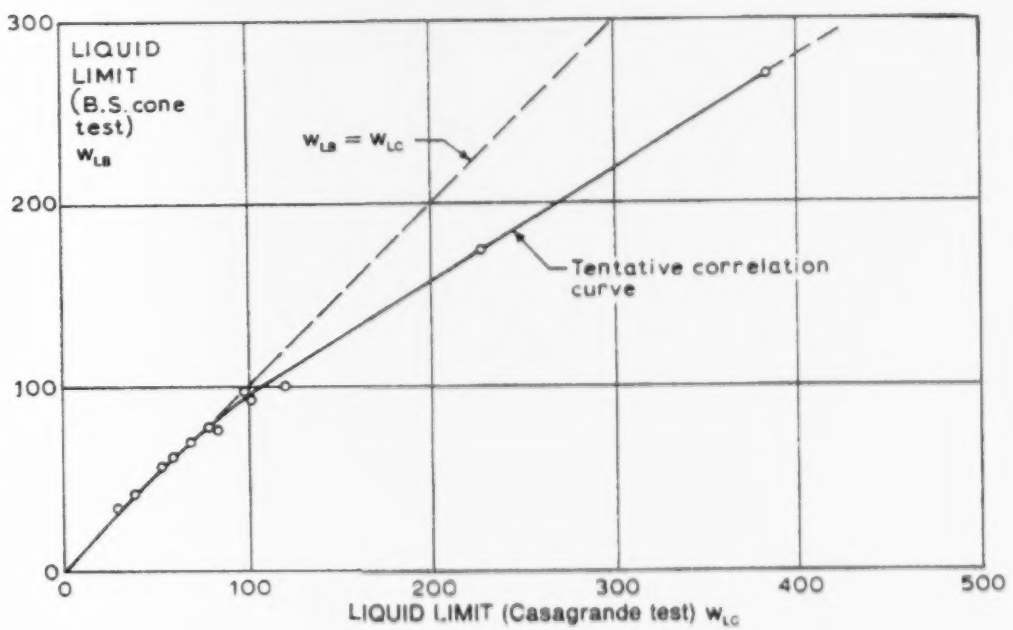

Figure 3.12 Correlation of Liquid Limit Results from Casagrande and Cone Methods (after Head, 1992)

Table 3.5 Comparisons of Casagrande and Cone Penetrometer Methods

Item	Casagrande Method	Cone Penetrometer Method
Cost of Equipment	Manually operated apparatus is less expensive and costs approximately $1000. Cost of motorised device with a revolution counter is almost 1.6 times that of a manually operated apparatus, and is comparable to the cost of a cone penetrometer.	Costs almost twice that of manually operated Casagrande apparatus.
Wear of Equipment	Base and cup wear quickly and require replacement after about every fifty tests. Replacement of these items is expensive.	Only item that wears is cone and the rate of wear is generally very small. The cone is inexpensive to replace.
Equipment Calibration	Several checks and adjustments are involved before each test and require experienced and skilled operator.	No major calibrations are involved before each test.
Speed of Testing	Testing Including preparation of sample requires three days.	May not be quicker than Casagrande method.
Sensitivity of the Test Method	Sensitive to small differences in apparatus, such as hardness of the base, wear of the cup, operator techniques, speed of operation and observation of point of groove closing. A subjective test compared to cone method.	Test results are not so dependent on the design of the apparatus or the manner in which it is used. The impact on the test results due to minor differences in surface texture, sharpness of the cone or operator techniques is very small.
Relationship to Engineering Properties	No difference.	No difference, and determines the same parameter as the Casagrande method.
Operator Training	Difficult to perform the test and requires considerable training.	Easier to perform the test and the operator can be trained easily.
Precision	Test results are equipment and operator dependent and difficult to reproduce.	Test results are more consistent, and less liable to experimental and personnel errors.

4. Test Data and Analyses

4.1 SOURCE OF SOIL SAMPLES AND METHOD OF PREPARATION

All together thirty-four samples were tested for this study. Twenty-five of these samples were from inorganic clayey soils that have been found in the Province of Ontario. These samples were collected from boreholes that were drilled as a part of the foundation investigations carried out by the Pavements and Foundations Section for in-house projects. The samples that were tested, with the exception of Sample No. 30007N, may be classified as low to medium (CL to CI) plastic clays. These materials represent glacial and post-glacial clays and silts typical of those found in Ontario and much of the northeastern USA.

The inorganic clayey soils collected in the Province of Ontario have provided data on correlation between the two methods up to a liquid limit value of 59. To extend the range of correlation into the highly active and high plastic clays, commercially available Bentonite and Kaolinite clays were mixed in various proportions and tested to obtain liquid limits ranging from 60 to 441.

Most of the samples were prepared in accordance with the dry preparation method described in Section 10.2 of ASTM D 4318, and this has been the consistent practice of the Ministry of Transportation. Only a few samples were either prepared by the wet preparation method described in Section 10.1.2 of ASTM D 4318 or tested in their natural state. The preparation method of the samples is identified by a letter (N for natural state, A for air dried, or O for oven dried at 60° C), which is followed by the sample number.

4.2 CONE PENETROMETER RESULTS FROM DIFFERENT OPERATORS

The study conducted by the Soils and Aggregates Section in 1981 (Report EM – 41) concluded that greater accuracy could be obtained by the use of the cone penetrometer method. A cone weighing 80 grams, with a cone angle of 30° fabricated in the MTO machine shop was used in that study. The moisture content values corresponding to a 15-mm depth of penetration into the soil were compared to verify whether consistent results are obtainable by the cone method. Four experienced technicians designated as A to D performed the tests using the same equipment, and their results are shown in Table 4.1.

Reproducibility of results and technical skills required to determine the liquid limit by cone penetrometer were further investigated in this study by employing two experienced technicians (Tech. 4 and Tech. 3) and a student. The results obtained by them are given in Table 4.2.

Table 4.1 Cone Penetrometer Results from Four Technicians

Sample No.	Moisture Content at 15 mm				Liquid Limit			
	Tech. A	Tech. B	Tech. C	Tech. D	A	B	C	D
1	43.7	42.8	44.5	43.3	44	43	44	43
2	40.3	39.7	40.3	40.0	40	40	40	40
3	21.0	20.3	20.7	20.3	21	20	21	20
4	37.7	37.0	37.5	37.1	38	37	37	37

Table 4.2 Cone Penetrometer Results from Two Experienced Technicians and a Student

Sample No.	Moisture Content at 20 mm			Liquid Limit		
	Tech. 4	Tech. 3	Student	Tech. 4	Tech. 3	Student
2001	29.1	28.9	28.9	29	29	29
2002	23.4	23.8	23.6	23	24	24
2006	39.3	38.7	38.8	39	39	39
2009	30.3	29.9	30.1	30	30	30
2010	34.1	34.3	33.9	34	34	34

4.3 LIQUID LIMIT RESULTS DETERMINED BY CONE PENETROMETER AND CASAGRANDE METHODS

Two experienced technicians who have been routinely performing the Atterberg limits tests carried out the tests by both methods. The technician who started the sample preparation followed through all stages of the tests by both cone and Casagrande apparatus, in order to minimize the number of variables and to produce consistent results.

The Ministry of Transportation has been using a motorised Casagrande apparatus fitted with a revolution counter for several years. The Casagrande apparatus fitted with the revolution counter and a drive motor to crank the cam at the correct speed were used for this study. A cone penetrometer conforming to BS1377: 1990 shown in Figure 3.7 was used to perform the tests. The cone penetrometer used was fitted with a dial gauge to measure the depth of penetration to the nearest 0.01mm and an auto-timer to automatically re-lock the stem, 5 seconds after the release of the cone.

Samples for both methods were prepared in accordance with the procedures described in Section 10.0 of ASTM D 4318 and left overnight to mature. The tests at any particular moisture content of a sample were performed using both cone and Casagrande apparatus before adjusting the moisture content of the sample for a repeat of the test. This was accomplished by performing the test by the Casagrande method first; upon completion, the sample was thoroughly mixed and re-tested using the cone penetrometer.

Table 4.3 Liquid Limit Results by Cone and Casagrande Methods

Sample No.	Moisture Content Corresponding to		Liquid Limit	
	25 Blows	20 mm	Casagrande	Cone
20001O	28.0	29.4	28	29
20001N	28.6	28.9	29	29
20002N	22.6	23.8	23	24
20003N	28.9	30.2	29	30
20004N	33.2	34.3	33	34
20005N	25.1	26.9	25	27
20006O	39.0	39.3	39	39
20008N	22.8	23.8	23	24
20009O	28.4	29.8	28	30
20010N	33.6	34.3	34	34
20011N	36.9	37.6	37	38
20012N	25.0	25.6	25	26
20013O	19.1	20.4	19	20
20014N	28.6	28.7	29	29
00001A	19.0	20.0	19	20
30007N	58.9	56.9	59	57
50000O	32.0	32.9	32	33
50002O	24.6	26.5	25	26
50004O	43.6	43.8	44	44
50006O	35.9	39.1	36	39
50007A	16.1	18.0	16	18
50008O	22.6	24.4	23	24
50009O	22.9	24.9	23	25
70004O	20.0	21.8	20	22
70005A	15.2	18.3	15	18
01B-11006	59.6	60.1	60	60
01B-11007	132.1	118.6	132	118
01B-11008	157.6	141.0	158	141
01B-11009	72.8	70.3	73	70
01B-11010	81.3	77.1	81	77
01B-11011	90.9	87.9	91	88
01B-11012	97.5	90.6	97	91
01B-11013	109.6	109.4	110	109
01B-11014	441.0	316.0	441	316

The results from both test methods are given in Table 4.3. The information provided in this table includes moisture contents corresponding to 25 Blows (Casagrande method) and 20 mm depth of penetration (cone penetrometer method) as well as the liquid limits determined by both methods. As required by both test methods, the liquid limit is reported to the nearest whole number (ASTM D 4318, Section 19.1.4).

4.4 ANALYSIS OF TEST RESULTS

4.4.1 Repeatability and Reproducibility of Cone Penetrometer Method

The precision data published in ASTM D 4318 are used for comparison purposes and to evaluate the acceptability of the results obtained by the cone penetrometer method. The acceptable range of two liquid limit results reported in Section 20.1.2 of ASTM D 4318-00 for "Single Operator Results" (Within-Laboratory Repeatability) are based on three replicate tests performed by each Triplicate Test Laboratory on each soil type. Triplicate Test Laboratory in the Standard is identified as a laboratory that performed three triplicate tests per soil type. The acceptable ranges between two liquid limit results obtained by a single operator published in ASTM D 4318-00 are as follows:

Soil Type	Standard Deviation	Acceptable Range
CH	0.7	2
CL	0.3	1
ML	0.5	2

The maximum difference between two individual moisture content results in Table 4.1 ranges from 0.6 % to 1.7 %, but the maximum difference between two individual liquid limit results is only one. The liquid limit results reported in Table 4.1 are well within the acceptable range for Single Operator Results, even though these tests were performed by four different operators, and the cone penetrometer used was not standardised or automated.

The results shown in Table 4.2 indicate a maximum difference between two individual moisture content results in the range of 0.2 % to 0.6 %, and liquid limit results differing only in the case of Sample No. 2002 between Tech. 3 and Tech. 4 (by one). Such precision and consistent results may be attributed to the test method itself, and the automated and standardised cone penetrometer that was used in this study. In addition, the results obtained by the relatively inexperienced student are very consistent with the results obtained by experienced technicians. This suggests that the cone penetrometer method is quite simple, and the operators can be easily trained on it in contrast to the Casagrande apparatus. Further, the findings also indicate that consistent, repeatable and reproducible results can be obtained by the cone penetrometer method.

4.4.2 Correlation between Casagrande and Cone Penetrometer Methods

The relationship between the liquid limit results obtained from the cone and Casagrande methods is shown in Figure 4.1. The results indicate that below 40 %, the liquid limit determined by the cone method is slightly higher, i.e., by a value of 1 to 2, than that by the Casgrande method. The difference in results is insignificant compared to the acceptable range of values reported in the ASTM Standard. However, above 95 %, the cone method gives values lower than the results obtained by the Casagrande method. The relationship shown in Figure

4.1 indicates that for liquid limit values up to 95 % there is little or no difference between the liquid limits determined by each method.

The difference in liquid limit values above 95% may be attributed to the behaviour of high plastic clays when sheared by different methods. Often the liquidity index, LI, of high plastic clays with liquid limit above 90 will be higher than one. If the liquidity index is higher than one, the soil will be essentially a viscous liquid when sheared.

The definition of the liquid limit in the cone penetrometer method is dependent on the moisture content at which the soil acquires a shear strength value of 1.7 kN/m^2. The Casagrande procedure, on the other hand, is dependent on the moisture content at which the soil flows as a result of the impact induced by the fall of a cup. The difference in liquid limit determined by each method appears to be magnified above 95 %. The difference may be resulting from the soil behaviour, which depends on the method by which it is sheared.

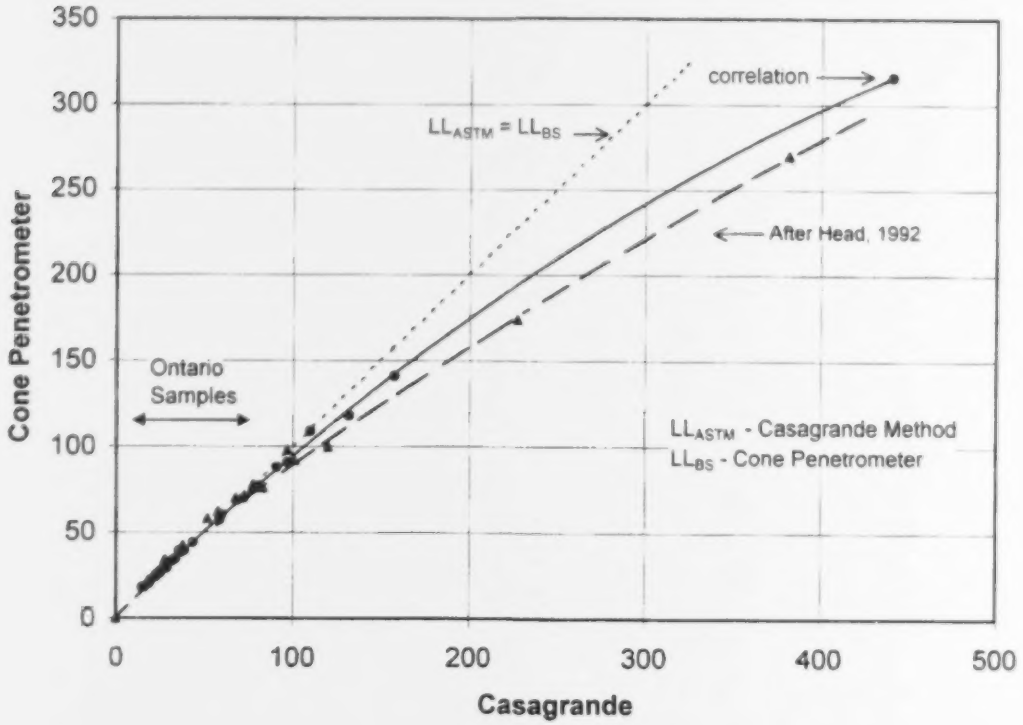

Figure 4.1 Correlation of Liquid Limit Results from Cone and Casagrande Methods for Ontario Clays (LL=16–59) and Bentonite Mix (LL=60–441)

5. Liquid Limit by One-Point Method

5.1 GENERAL BACKGROUND

The one-point method needs one moisture content measurement only, to determine the liquid limit of clayey soils. This method provides a quick means of determining the liquid limit, and the result is likely to be less reliable than the multi-point Casagrande or cone penetrometer method. The one-point method may not be valid for soils with liquid limit exceeding 120, and for such soils, the multi-point method using the appropriate amount of sample must be performed. In addition, the correlation on which the calculations of the one-point method are based may not be valid for organic soils or soils deposited in a salt- water environment.

The one-point method is useful as a rapid test procedure or when only a very small amount of sample is available, and when a result of lesser accuracy is acceptable. This test method should not be used in cases where test results may be subject to dispute or when the test is performed by an inexperienced operator.

5.2 FLOW CURVE

The 'Flow Curve' for a clayey soil is derived from the Casagrande method described in Section 3.2.4. Values of moisture content, W_n, are plotted against Log N, where N is the number of blows required to close the groove. The curve from this plot is known as the 'Flow Curve", which is a straight line over the range of values covered by a typical liquid limit test. The slope of the flow curve will be more or less the same for soils of similar geologic origin and clay mineralogy.

5.3 FACTOR FOR ONE-POINT METHOD

A plot of Log W_n against Log N gives a straight line inclined at an angle θ to the horizontal axis. The slope of this straight line, i.e., tan θ will depend on the type of soil and its geologic origin. According to Section 14.0 of ASTM D 4318, tan θ assumed for soils found in Ontario is equal to 0.121. In the British Standard, the corresponding value is 0.092.

The test results obtained by the Casagrande method were plotted on a logarithmic chart and further analysed to verify whether a value of 0.121 is appropriate for soils found in Ontario. In addition, the results from the cone penetrometer method were also analysed to determine a suitable value for tan θ.

5.3.1 Casagrande Method

The equation for the flow line shown in Figure 5.1 is given by:

$\tan \theta = (\text{Log LL} - \text{Log } W_n)/(\text{Log N} - \text{Log 25})$, by re-arranging

$\tan \theta = \text{Log } (LL/ W_n)/\text{Log } (N/25)$

$LL/ W_n = (N/25)^{\tan \theta}$, by re-arranging $LL = W_n (N/25)^{\tan \theta}$

$LL = L_f (W_n)$, where $L_f = (N/25)^{\tan \theta}$

W_n = moisture content corresponding to blow count N

LL = liquid limit of the soil sample

L_f = the factor

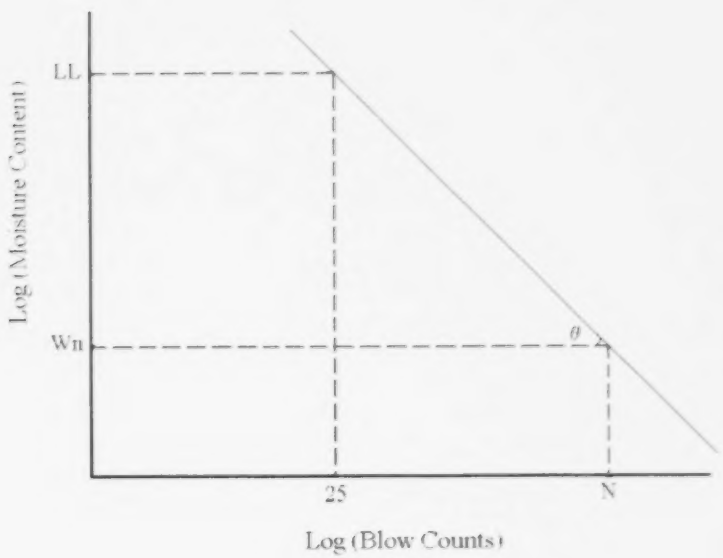

Figure 5.1 Flow Line on a Logarithmic Chart (Casagrande Method)

The plots of Log W_n against Log N for each sample are included in the Appendices A1 to A8. The slopes of the flow lines, tan θ, computed from these plots for soils found in Ontario are given in Table 5.1.

The type of soils, with the exception of Sample No. 30007N, that were tested can be classified as low (CL, LL<35) to medium plastic (CI, 35<LL<50) clays. The liquid limit values reported are typical of the majority of clays found in Ontario. The slope angle, tan θ, may vary depending on the type of soil and its geologic origin. In view of this, the tan θ values provided in Table 5.1 were plotted against liquid limit in the form of a scatter plot as shown in Figure 5.2.

The plot does not indicate any particular trend and the majority of the points are located between the values used by the British Standard (0.092) and ASTM D 4318 (0.121). A mean line drawn through these points results in an intercept of y = 0.108. Based on the data available, a slope angle given by tan θ equal to 0.108 may be assigned for soils that have been tested.

Table 5.1 Slope of Flow Lines from Casagrande Method

Sample No.	Liquid Limit	tan θ	Sample No.	Liquid Limit	Tan θ
20001O	28	0.1121	00091A	32	0.0830
20001N	29	0.1235	00028A	30	0.0784
20003N	29	0.1199	00052A	30	0.1132
20004N	33	0.1129	00080A	30	0.0869
20005N	25	0.1322	30007N	59	0.0998
20006O	39	0.1105	50000O	32	0.1064
20008N	23	0.1371	50004O	44	0.1011
20010N	34	0.0883	50006O	36	0.1260
20011N	37	0.1182	50007A	16	0.1033
20012N	25	0.0940	50008O	23	0.1258
20013O	19	0.1081	50009O	23	0.1200
20014N	29	0.1030	70004O	20	0.1106
0001A	19	0.1000	70005A	15	0.1437

The difference between the ASTM value (0.121) that is being used by MTO and the value from this study (0.108) is only 12 %. The liquid limit is always reported to the nearest whole number, and this method of determination is used only when results of less accuracy are acceptable. Variation in the order of 12 % in the value of tan θ is not expected to significantly affect the liquid limit determined by this method. This is also evident from the factors provided in Table 5.2 for obtaining liquid limit from moisture content and blow counts required for causing the closure of the groove.

Table 5.2 Factors for Obtaining Liquid Limit by One-point Method Using Casagrande Method

No. Of Drops N	Factor L_f	
	ASTM	Suggested
20	0.973	0.976
21	0.979	0.981
22	0.985	0.986
23	0.990	0.991
24	0.995	0.995
25	1.000	1.000
26	1.005	1.004
27	1.009	1.008
28	1.014	1.012
29	1.018	1.016
30	1.022	1.020

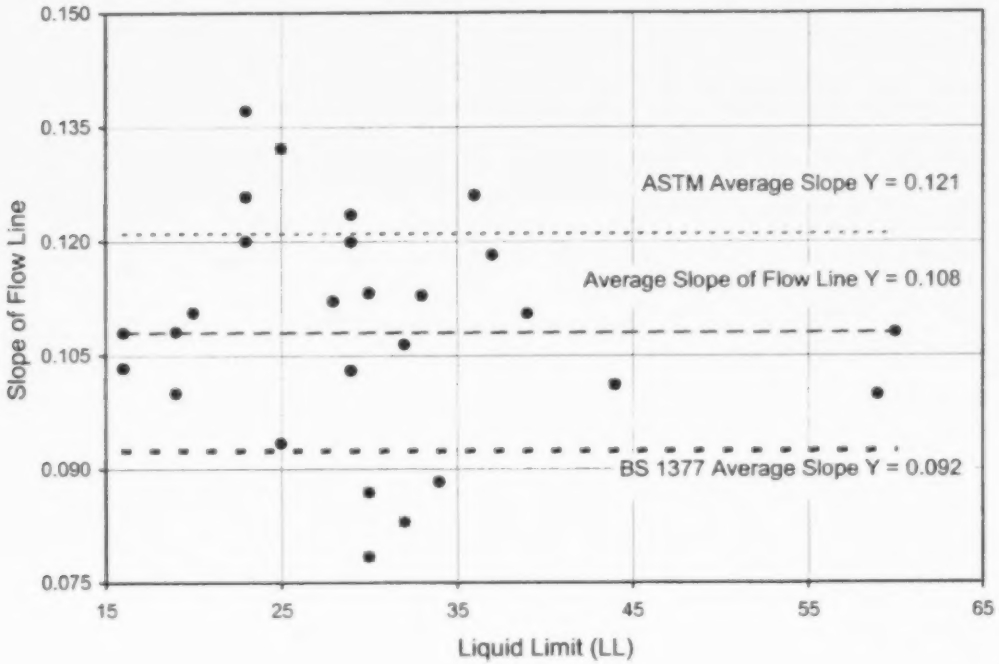

Figure 5.2 Relationships between Slope Angle (tan θ) and Liquid Limit Obtained by Casagrande Method for Ontario Clays

5.3.2 Cone Penetrometer Method

The one-point cone penetrometer method was initially introduced (Clayton, 1978) as a possibly less elaborate routine method. The factors recommended by Clayton are based on a statistical analysis of experimental data. In this test procedure, the moisture content of the soil sample must be adjusted so that a cone penetration of between 15 mm and 25 mm is obtained.

The factors currently used by BS 1377: 1990 to obtain liquid limit depend upon whether the soil is low (CL, LL<35), medium (CI, 35<LL<50) or high (CH, LL>50) plastic clay. Based on the information provided in BS 1377, the mean slope angle, tan θ, was computed for each soil type. The computed values are as follows:

Soil Type	Tan θ
CH	0.355
CI	0.337
CL	0.263

The test results obtained by the cone penetrometer method are plotted on a logarithmic chart, i.e., Log W_d Vs Log D, as shown in Figure 5.3. The equation for the flow line shown in Figure 5.3 is given by:

$\tan \theta = (\text{Log LL} - \text{Log } W_d)/(\text{Log } 20 - \text{Log D})$, by re-arranging

$\tan \theta = \text{Log}(LL/ W_d)/\text{Log}(20/D)$

$LL/ W_d = (20/D)^{\tan \theta}$, by re-arranging $LL = W_d (20/D)^{\tan \theta}$

$LL = L_{fc} (W_d)$, where $L_{fc} = (20/D)^{\tan \theta}$

W_d = moisture content corresponding to depth of penetration D into the soil

LL = liquid limit of the soil sample

L_{fc} = the Factor

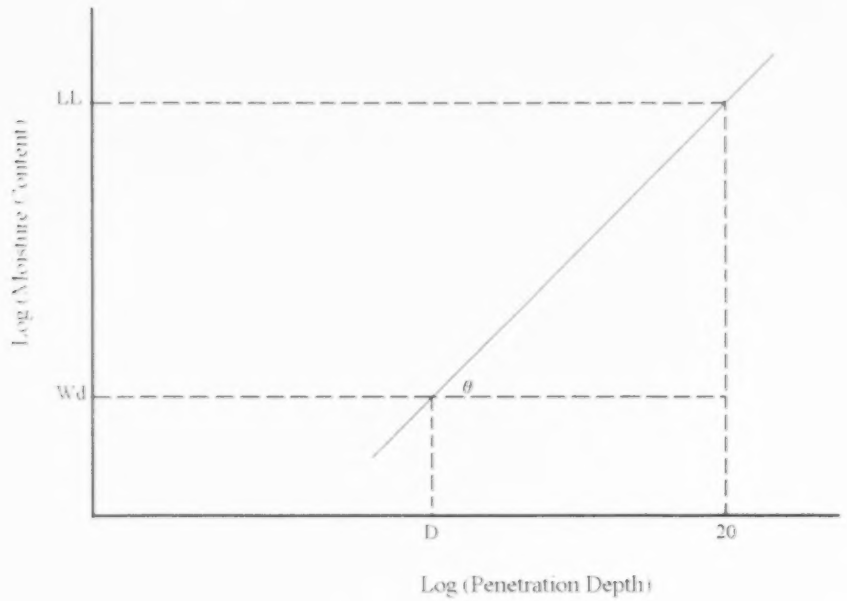

Figure 5.3 Flow Line on a Logarithmic Chart (Cone Method)

The plots of Log W_d against Log D for each sample are included in the Appendices B1 to B9. The slopes of the flow lines, tan θ, computed from these plots for soils found in Ontario are given in Table 5.3.

All of the samples, with the exception of Sample No. 30007N, that were tested fall in the soil classification of low to medium plastic clay. The tan θ values provided in Table 5.3 were plotted against liquid limit in the form of a scatter plot, as shown in Figure 5.4. The plot does not indicate any particular trend with respect to liquid limit or soil classification. This may be due to the fact that the data are from a limited number of soil samples with liquid limit ranging from 15 to 59. Most of the points in the plot are located between 0.290 and 0.465. A mean line drawn through the points plotted indicates an intercept of 0.366. Based on the findings, an

average slope angle given by tan θ equal to 0.366 is assigned for the soils that have been tested.

Table 5.3 Slope of Flow Lines from Cone Penetrometer Method

Sample No.	Liquid Limit	tan θ	Sample No.	Liquid Limit	Tan θ
20001O	29	0.3630	20013O	20	0.5443
20001N	29	0.3707	20014N	29	0.4024
20002N	24	0.4378	0001A	20	0.3797
20003N	30	0.2969	30007N	57	0.3286
20004N	34	0.2889	50000O	33	0.4172
20005N	27	0.3727	50004O	44	0.2579
20006O	39	0.3050	50006O	39	0.5110
20008N	24	0.4657	50007A	18	0.3360
20009O	30	0.4334	50008O	24	0.3184
20010N	34	0.3761	50009O	25	0.3175
20011N	38	0.3390	70004O	22	0.3469
20012N	26	0.4224	70005A	18	0.2373

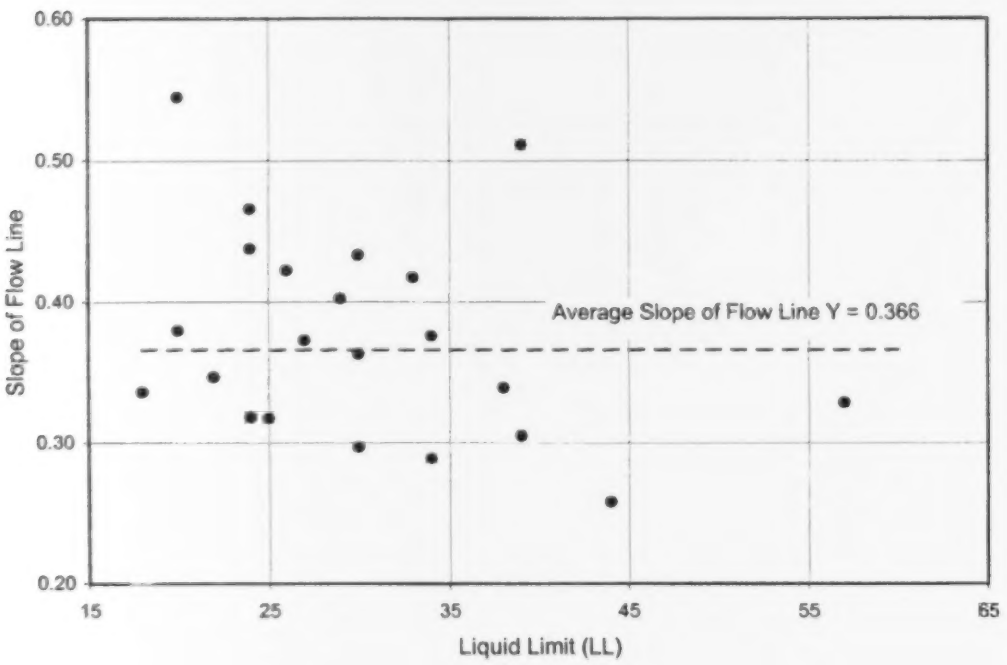

Figure 5.4 Relationships between Slope Angle (tan θ) and Liquid Limit Obtained by Cone Method for Ontario Clays

As indicated in Section 5.3.2, the one-point method of determination is used only when results of less accuracy are acceptable. Therefore, a refined analysis or detailed testing program may

not be warranted. The factors for obtaining liquid limit from moisture content and depth of penetration, computed on the basis of a tan θ value of 0.392, are given in Table 5.4.

Table 5.4 Factors for Obtaining Liquid Limit by One-point Method Using Cone Penetrometer Method

Penetration Depth in mm	Recommended Factor (L_{fc})
15	1.111
16	1.085
17	1.061
18	1.039
19	1.019
20	1.000
21	0.982
22	0.965
23	0.950
24	0.935
25	0.921

6. Conclusions

Based on the findings from this study and the observations made by other agencies, the following conclusions are made:

- The cone penetrometer is easy to operate and the test method is easy to perform, compared to the Casagrande test procedure.
- There is less possibility for errors due to calibration or mechanical adjustment of the cone penetrometer compared to the Casagrande method.
- The cone penetrometer gives a greater degree of precision, repeatability and reproducibility.
- Below a liquid limit value of 95, there is insignificant difference between the results obtained by the Casagrande and cone penetrometer methods. All known Ontario soils have values within this range.
- A mean slope angle, tan θ, value of 0.108 for the flow line obtained by the Casagrande method appears to be appropriate for soils found in Ontario. However, the difference between the value that is being used (0.121) and the value suggested (0.108) is too insignificant to influence the liquid limit result obtained by the one-point method.
- A mean slope angle, tan θ, value of 0.366 for the flow line obtained by the cone penetrometer appears to be appropriate for clayey soils found in Ontario.
- There is no clear relationship or trend exists between the slope angle and the low to medium plastic clays studied.

7. Recommendations

1. The difference between the liquid limit determined by the cone penetrometer and Casagrande apparatus for soils found in Ontario is insignificant. The cone penetrometer method is recommended for adoption as an alternate to MTO LS-703, Multi-Point Method A (Casagrande apparatus).

   The anticipated benefits are as follows: the equipment is more robust, less susceptible to operator technique and experience resulting in greater accuracy, and is judged to give improved multi-laboratory precision.

2. The one-point method of liquid limit determination is used only when a result of lesser accuracy is acceptable. The cone penetrometer method is recommended for adoption as an alternate to MTO LS-703, One-Point Method B (Casagrande apparatus). The factors provided in Table 5.4 are recommended for use in conjunction with the cone penetrometer method for determination of liquid limit by the one-point method.

   The factors recommended for the cone penetrometer method represent the soils found in Ontario and their geologic origin. This benefits the user to determine the liquid limit by one-point method more close to the multi-point method.

8. Acknowledgements

The author wishes to acknowledge the assistance and dedicated work of the laboratory staff of Soils and Aggregates Section in preparation of samples and performing the tests. We received considerable assistance from Faizul Bacchus and Peter Corsaro in collecting soil samples and planning the testing program. In particular, the efforts of Peter Corsaro and Julia Gabriele are gratefully acknowledged.

Mr. Bala Tharmabal, Manager, Bridge Office and the staff of Pavements and Foundations Section are also gratefully acknowledged for their review comments and suggestions.

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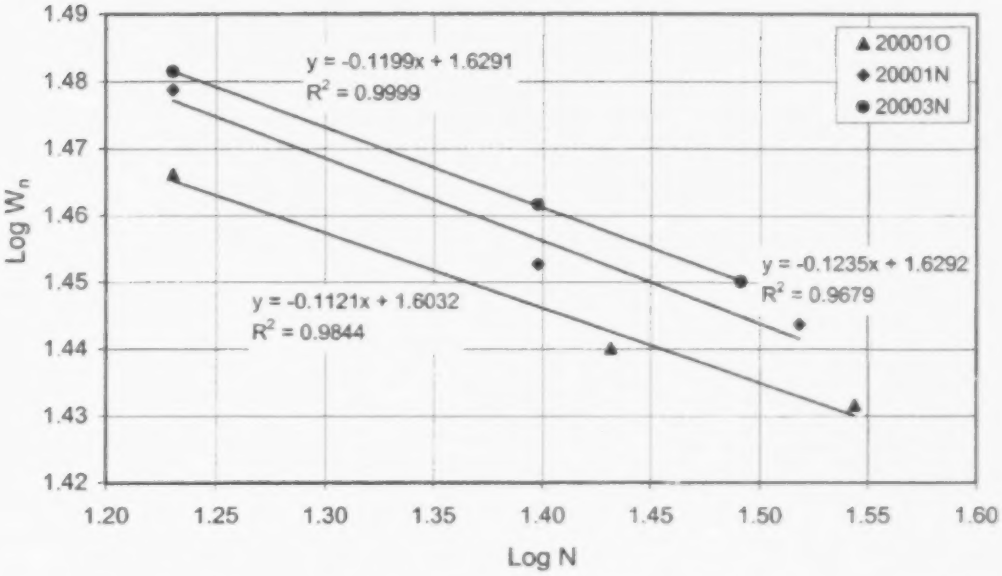
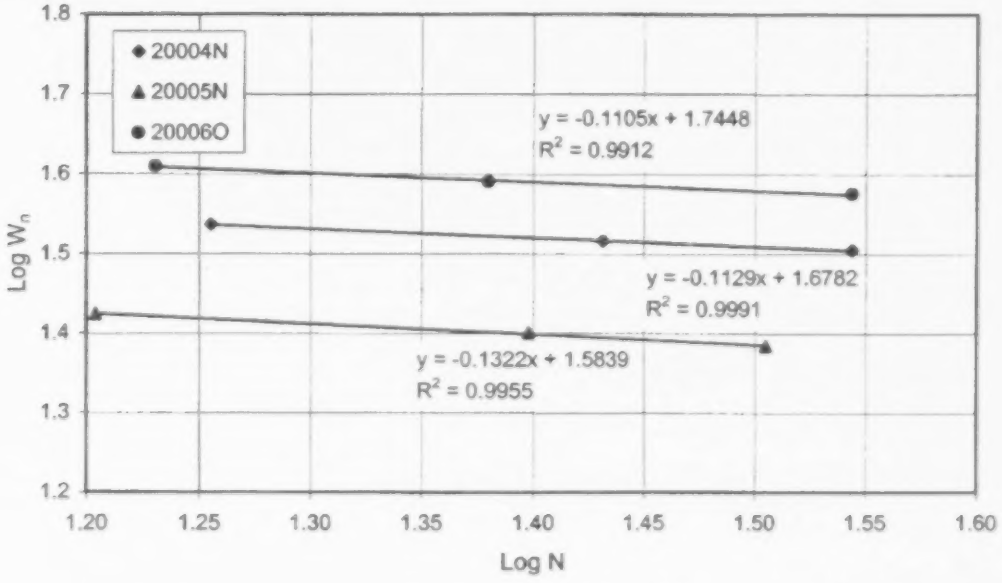
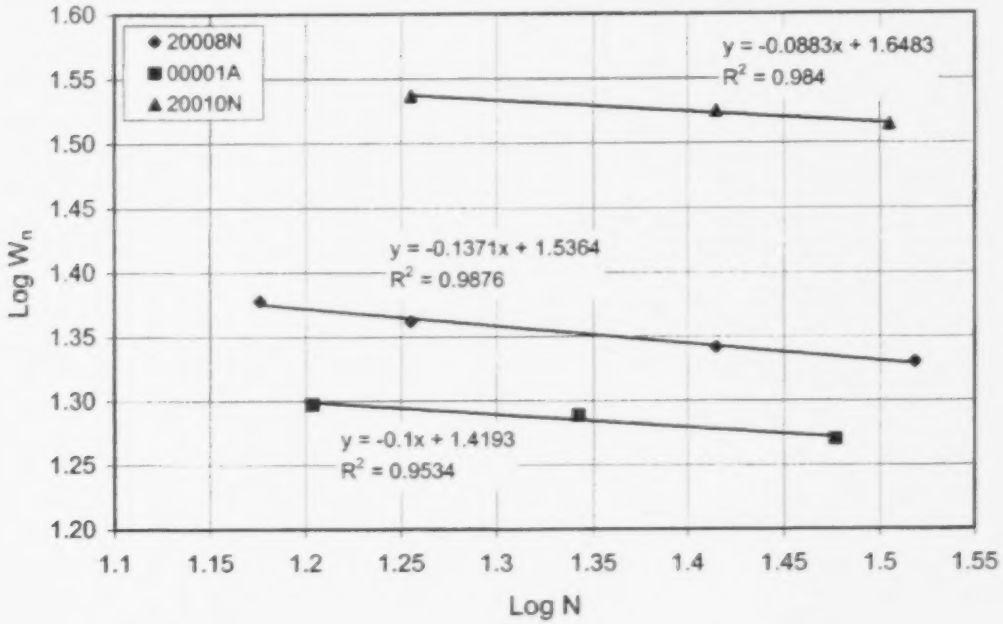
Appendix A: Results Obtained by Casagrande Device for Ontario Clays



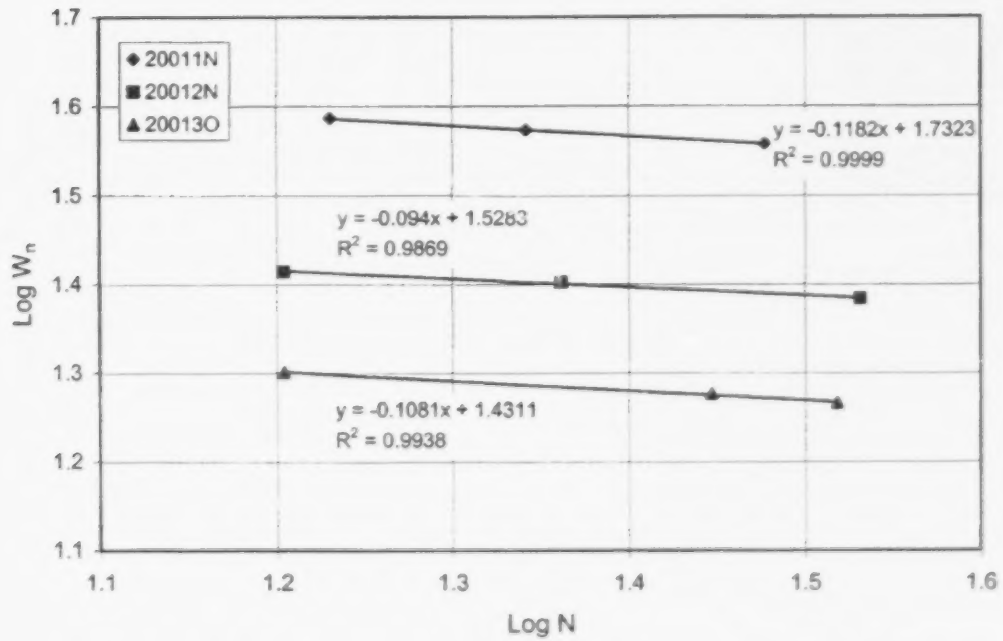
Appendix A.1 Results for Samples 20001O, 20001N & 20003N



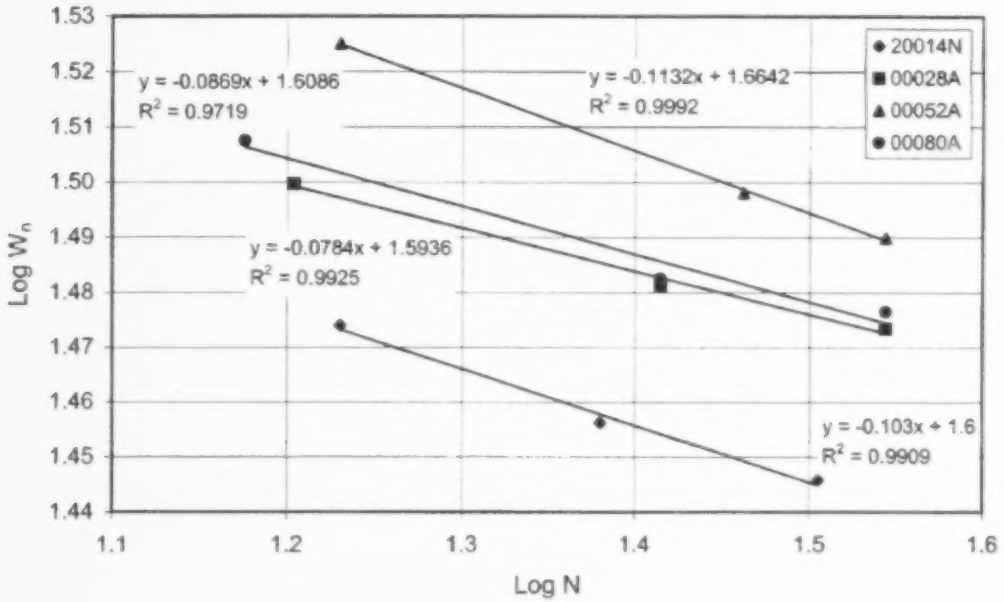
Appendix A.2 Results for Samples 20004N, 20005N & 20006O



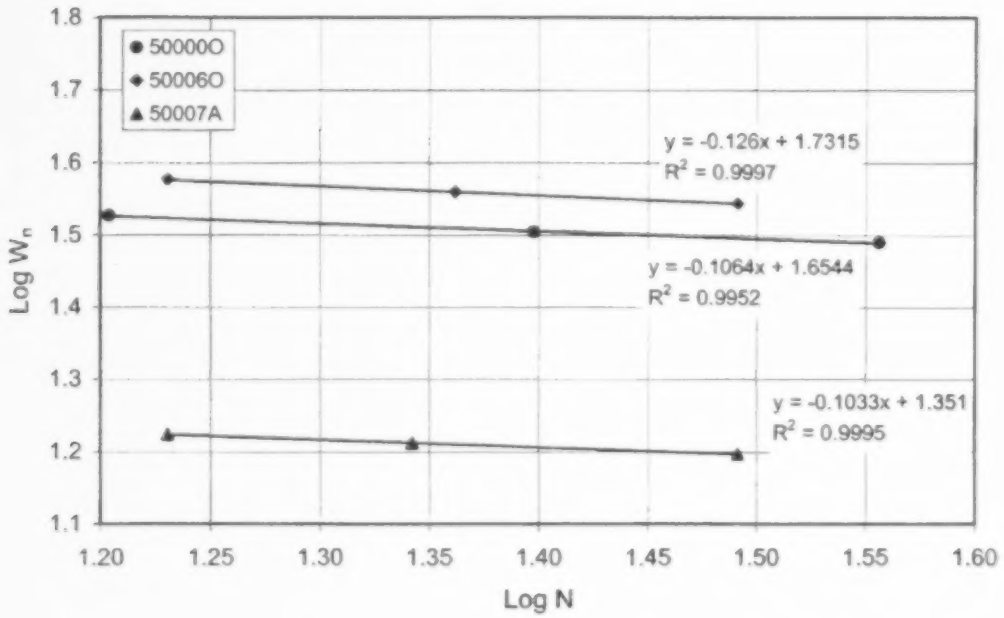
Appendix A.3 Results for Samples 20008N, 00001A & 20010N



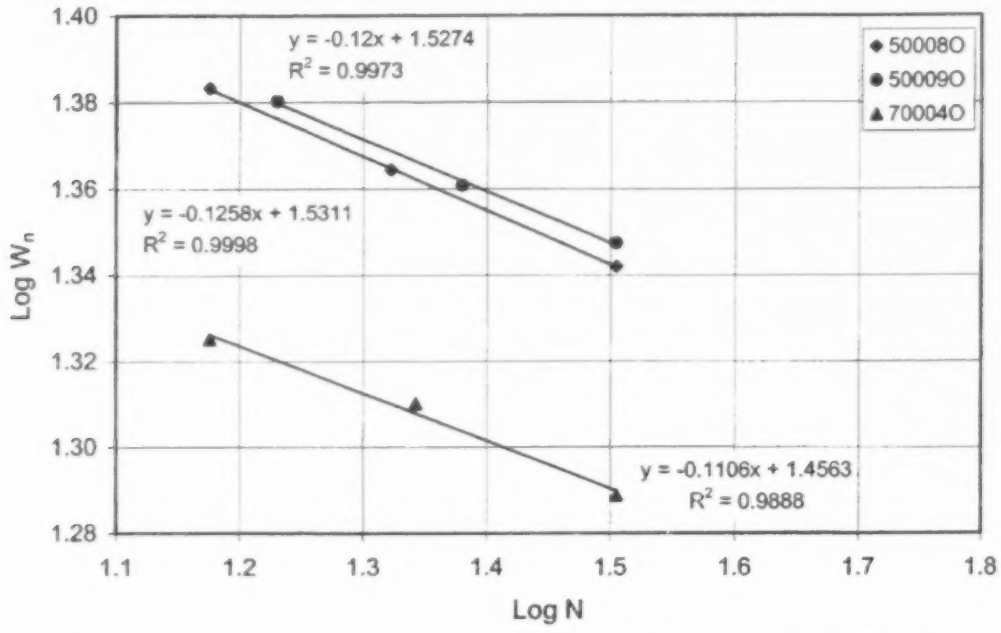
Appendix A.4 Results for Samples 20011N, 20012N & 20013O



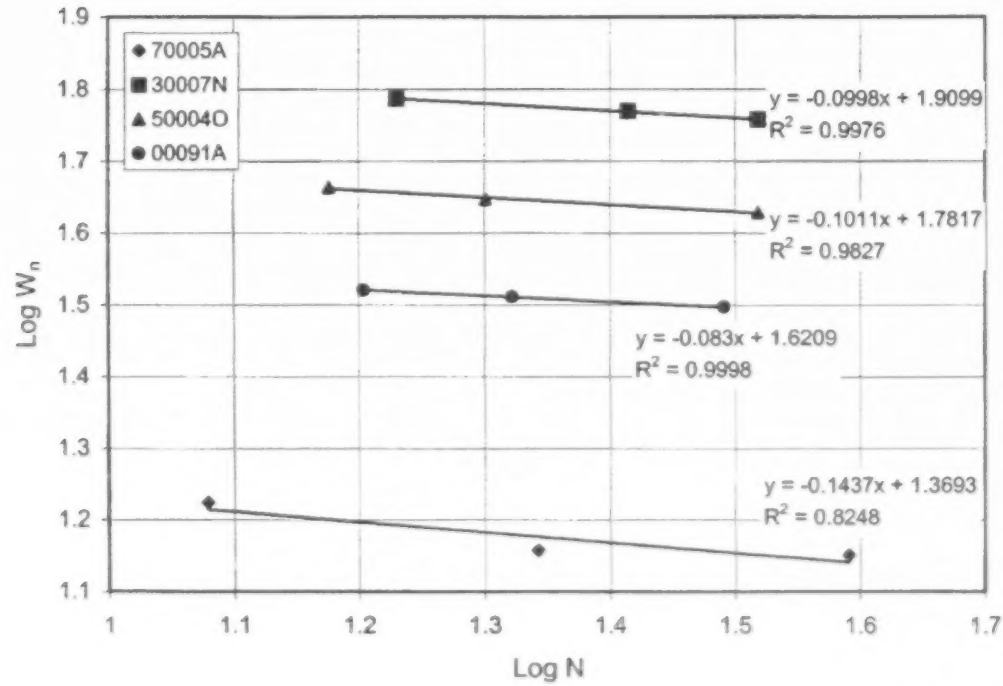
Appendix A.5 Results for Samples 20014N, 00028A, 00052A & 00080A



Appendix A.6 Results for Samples 50000O, 50006O& 50007A

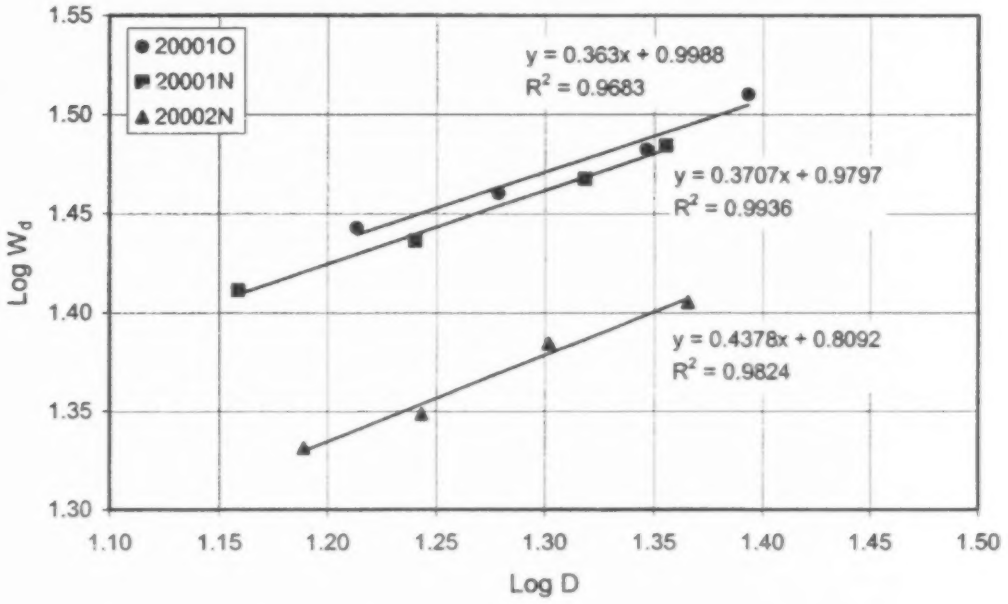


Appendix A.7 Results for Samples 50008O, 50009O& 70004O

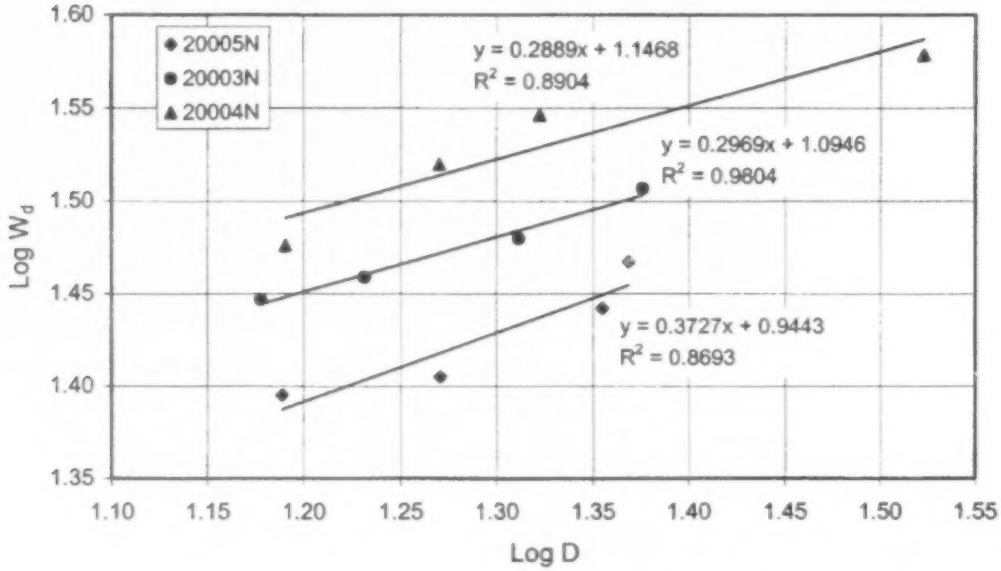


Appendix A.8 Results for Samples 70005A, 30007N, 50004O & 00091A

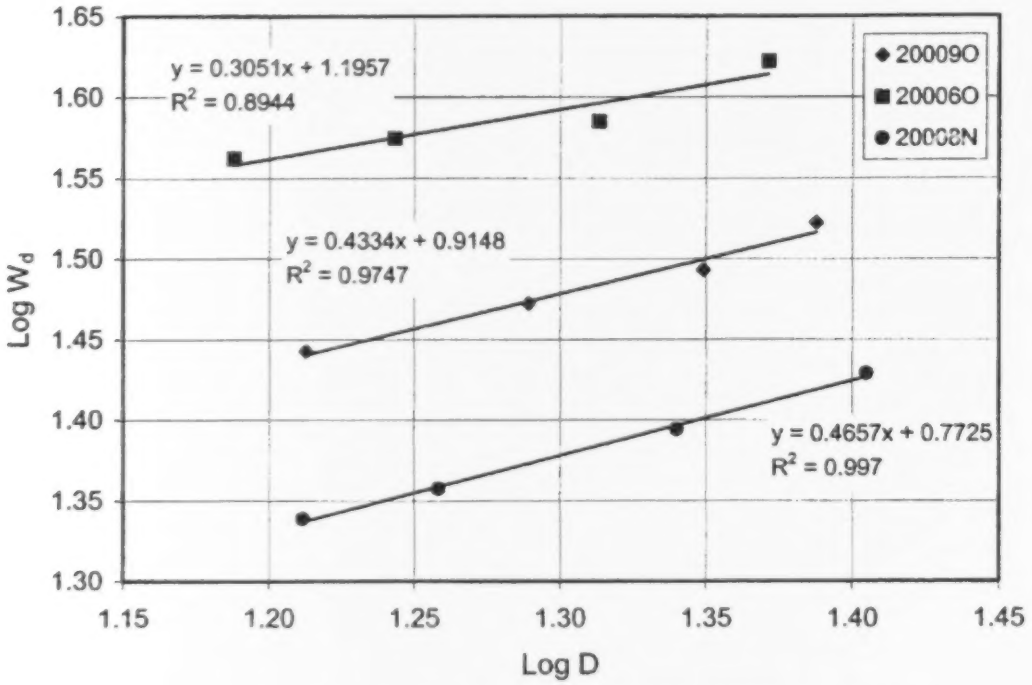
Appendix B: Results Obtained by Cone Penetrometer for Ontario Clays



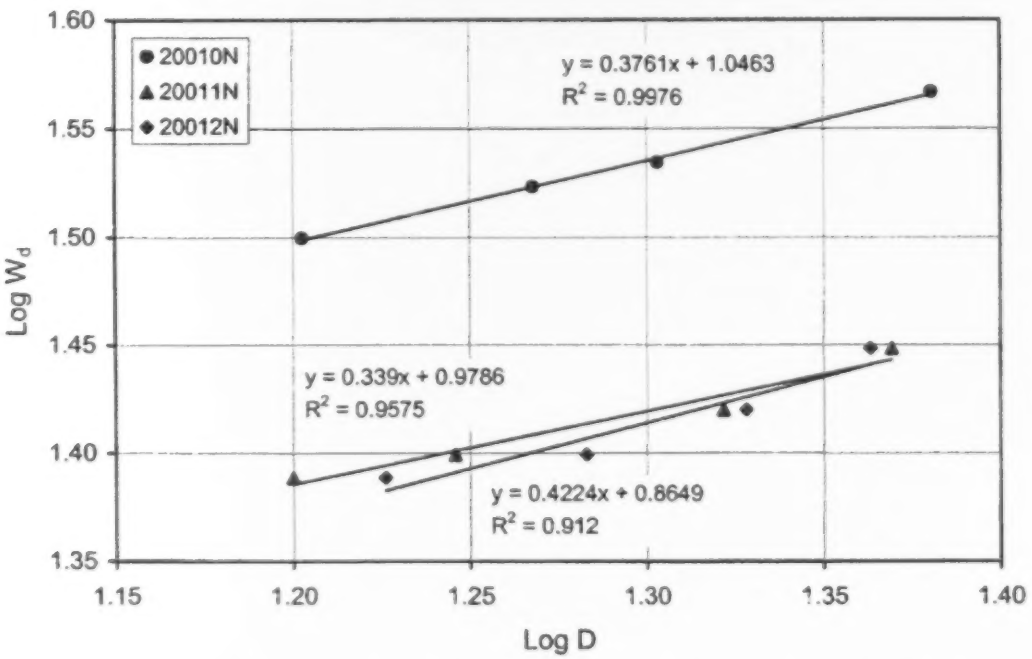
Appendix B.1 Results for Samples 20001O, 20001N & 20002N



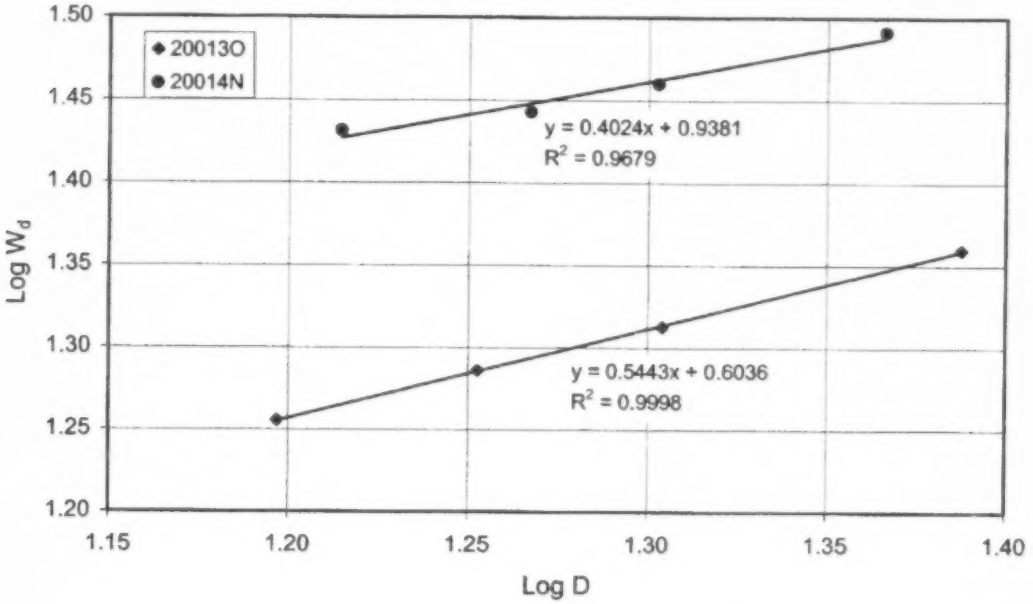
Appendix B.2 Results for Samples 20003O, 20004N & 20005N



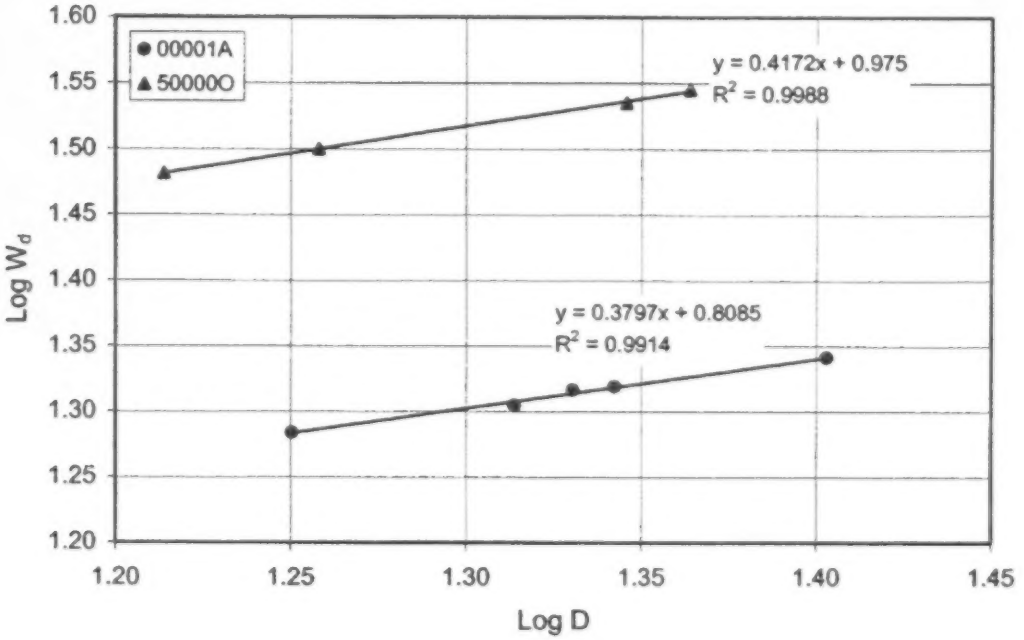
Appendix B.3 Results for Samples 20006O, 20008N & 20009O



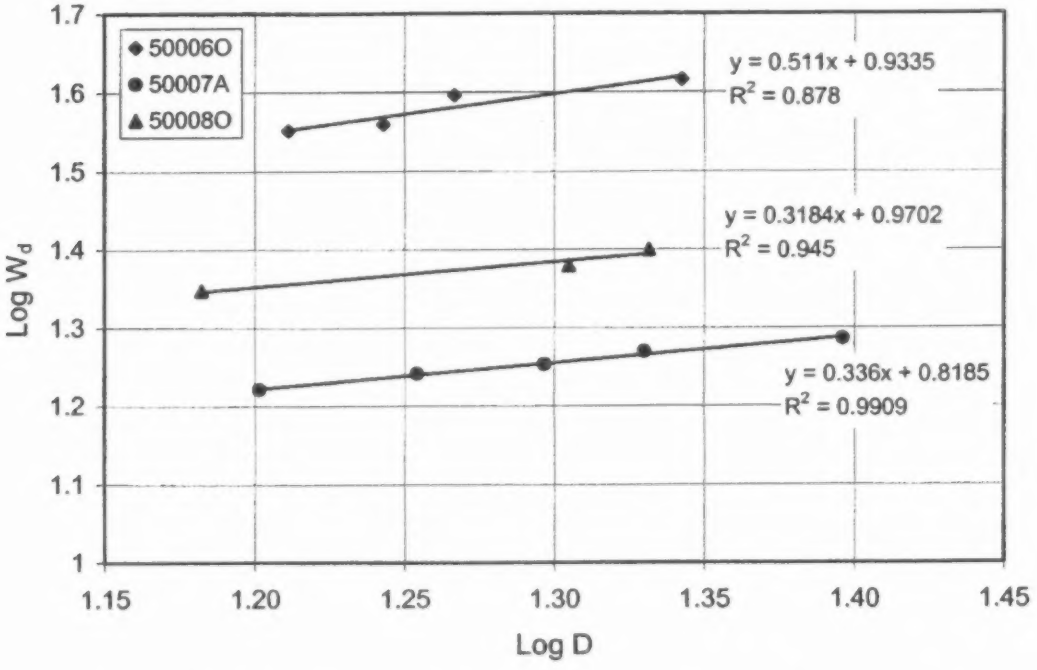
Appendix B.4 Results for Samples 20010N, 20011N & 20012N



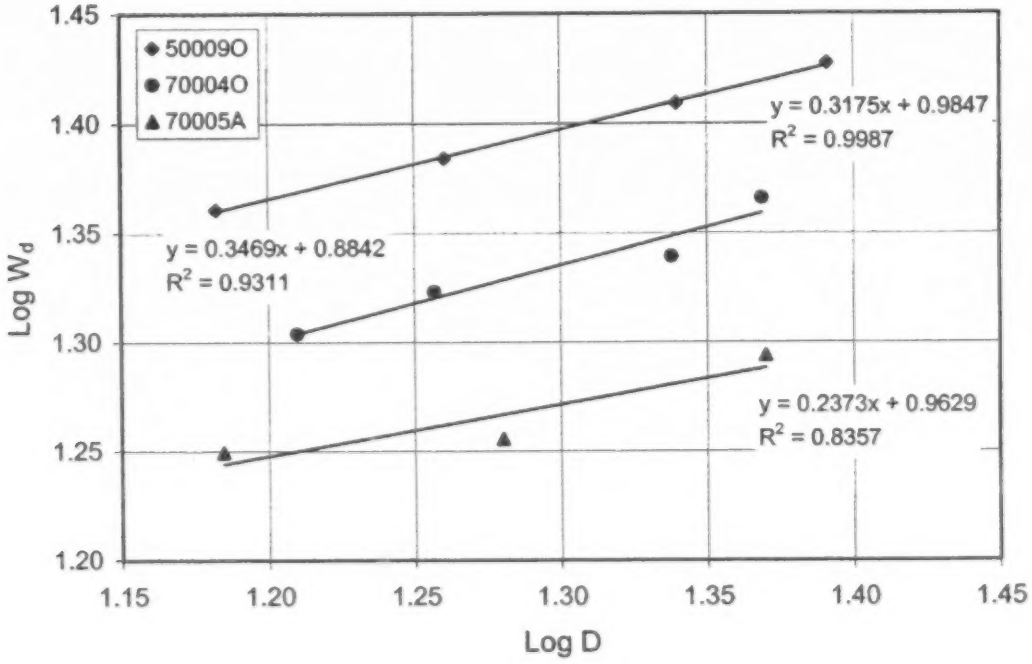
Appendix B.5 Results for Samples 20013O &20014N



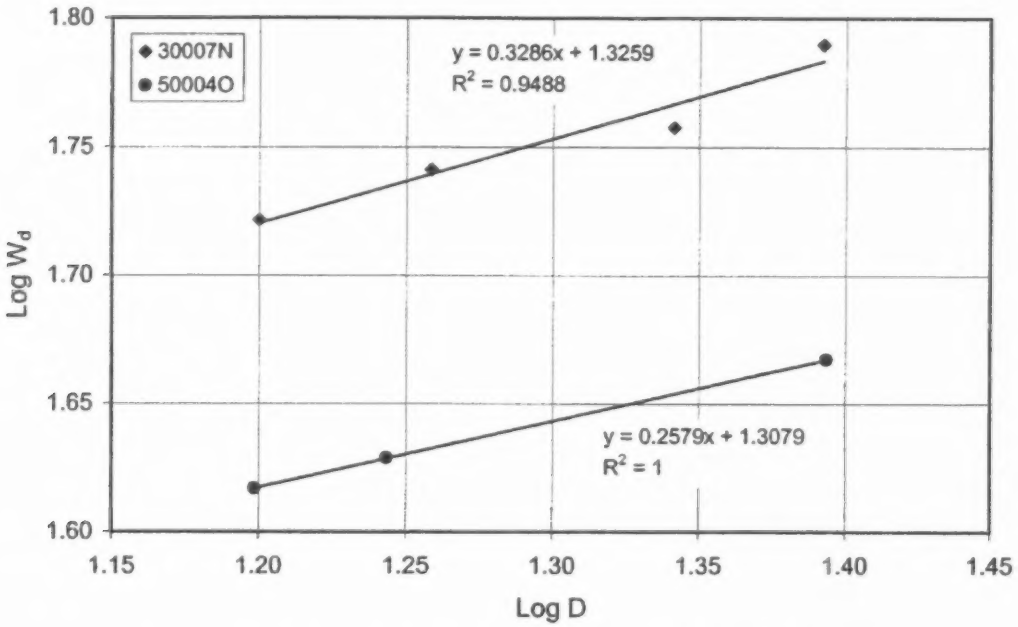
Appendix B.6 Results for Samples 00001A & 50000O



Appendix B.7 Results for Samples 50006O, 50007A & 50008O



Appendix B.8 Results for Samples 50009O, 70004O & 70005A



Appendix B.9 Results for Samples 30007N & 50004A